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Proceedings of

TRANSPAC 84

Rail··Bus··New Technology

The Second International Symposium on Advanced Propulsion and Control for Urban Transit

March 4–7, 1984

Sponsored by

U.S. DEPARTMENT OF TRANSPORTATION
URBAN MASS TRANSPORTATION ADMINISTRATION
Office of Technical Assistance

COD

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Conference Officers

Chairman	Steven A. Barsony
Program Coordinators	Ronald D. Kangas Robert C. Hoyler Patrick J. Sullivan
Technical Advisor	Louis A. Frasco
Conference Manager	Ellen Witt Dewey

FOREWORD

The following are the final proceedings of TRANSPAC '84, the Second International Symposium on Advanced Propulsion and Control for Urban Transit, held on March 4-7, 1984 in Baltimore, MD. These proceedings contain the complete collection of papers that were presented as well as transcriptions of the symposium panel sessions. The proceedings include presentations by both transit operators and equipment suppliers.

About four years ago in February 1980 in Washington, D.C., we sponsored our initial conference in this important area. At that time, we were embarking on our own program and recognized the need to call together members of the international transit community - both operators and suppliers - to discuss the technological and operational issues surrounding advanced propulsion development and deployment. The UMTA program in this area - AC propulsion for rail transit - is progressing satisfactorily and is about to enter the vehicle prototype testing phase.

This year, the scope of the original symposium has been expanded to include, in addition to advanced propulsion and control for fixed guideway, urban transit bus propulsion subsystems. The purpose was to provide a forum to present and discuss the latest developments and applications of propulsion technology and vehicular control in all forms of urban transit. The symposium established a natural forum which emphasized technological content and operational issues. The speakers were asked to de-emphasize specific product marketing in their presentations and panel discussions, relegating this aspect to the exhibit area.

The symposium organizing committee and the technical advisor wish to thank all the speakers and panel members for their professional commitment and enthusiastic support of the symposium. As these proceedings clearly demonstrate, the quality of the invited papers and panel sessions was exceptional. We also wish to extend our thanks to the suppliers for supporting the symposium with excellent exhibits of related hardware and product descriptions. Finally, we wish to acknowledge transit professionals from all aspects of the business for their enthusiastic support and attendance during the symposium.

Steven A. Barsony, Symposium Chairman
The U.S. Department of Transportation
Urban Mass Transportation Administration

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U.S. DEPARTMENT OF TRANSPORTATION OPENING ADDRESS

Steven A. Barsony

Peter Benjamin

U.S. DOT, URBAN MASS TRANSPORTATION ADMINISTRATION, OFFICE OF TECHNICAL ASSISTANCE

Good morning. My name is Steve Barsony. I will be Chairman of this international symposium. On behalf of the Department of Transportation, Urban Mass Transportation Administration, I would like to welcome all of you to the Second International Symposium on Advanced Propulsion and Control for Urban Transit.

I want to extend a special welcome to guests who are here representing some of the finest transportation companies in the world. Represented at this year's conference are West Germany, Japan, Canada, France, Finland, Belgium, Great Britain, Sweden and the United States. We are very pleased to have you and to have the opportunity to hear the progress of your research and development activities.

I must express a special welcome to some of the guests who have joined us here. The General Manager of the Baltimore Transit System and the Baltimore Mass Transit Administrator, Dave Wagner, is our keynote speaker. Dr. Peter Schmidt, who is Director of the Engineering Development Division of the Baltimore Transit Metro, was tremendously helpful in the preparation of this symposium. Both of these gentlemen are responsible for operating the Baltimore Metro Rapid Transit System, which we will be viewing toward the end of our stay. We hope the weather will have improved by then.

I recognize familiar faces this morning. Many of you are friends from way back and many of you were present at the first conference in Washington, D.C., four years ago. At that time, the Office of Technical Assistance was embarking on its own program in Advanced Propulsion Systems for rail transit and we realized that we needed to hear what members of the international transit community were saying about technology and operational issues. Our developmental program in AC propulsion for rail transit has progressed and is about to enter the vehicle testing phase at our testing facility in Pueblo. This will be followed by a revenue service demonstration at New York City Transit Authority (NYCTA), our host property. The program will be reported in detail in the Advanced Propulsion System session.

As you are aware, we have extended the scope of the symposium to include in addition to advanced propulsion and control for rail systems, advanced propulsion for urban bus transit systems. We have tried to avoid parallel sessions. Today there will be plenary sessions on the role of technology through innovation in the transit marketplace; rail and bus operational experience; transit system compatibility; and the use of solid-state electronics in propulsion and supply. Tomorrow, separate sessions will be held on the operational experience and technical description of related equipment.

We have added new areas to this year's agenda. The emphasis of the symposium is directed toward the latest developments and application of propulsion technology and vehicular control, for example, solid-state components for power conditioning, new designs based on these components, alternative fuels, engine and transmission improvements and issues of transit system compatibility.

Products and services used throughout the transit community today are truly of an international content. Domestic and foreign suppliers are continually competing at this international market. Scratch the surface of any major transit undertaking, bus or rail car, or the infrastructure itself and you find product and construction techniques of both domestic and foreign origin. We are convinced that our development work in the AC propulsion will help to improve reliability, lower the current maintenance cost and energy consumption of rapid transit systems. We are also looking forward to a renewed presence in the international market. I believe this forum for technological content and operational issues can promote a competitive spirit. We have de-emphasized specific product marketing in presentations and panels, but we have a number of hardware exhibits representing both foreign and domestic manufacturers.

In preparing for the symposium, we tried to maximize interaction and the long-term benefits to you as the participant. Our guidelines for the symposium require that the equipment or the techniques described must be either recently deployed or scheduled for near-term introduction. The distinguished collection of papers to be presented was distributed in advance to allow you to become familar with presentations of particular interest. We believe this approach will permit more time to be devoted to open discussions and question and answer periods. After the conference the complete proceedings of the symposium will be published.

Speaking now on behalf of the Symposium Organizing Committee and Technical Advisor, I want to thank all of the speakers and panel members for their professional commitment and enthusiastic support. The quality of the invited papers is exceptional. I also wish to thank all the suppliers for supporting the symposium with excellent exhibits of related hardware and product descriptions.

Last but not least I wish to acknowledge the excellent work of Ellen Witt Dewey, Conference Manager, and Lou Frasco of Frasco & Associates, the Technical Advisor without whom this symposium could not have taken place.

I encourage your active participation in the coming sessions and I wish to you all, an enjoyable, and educational, three days in and around the City of Baltimore. I encourage you to actively support the new technology developments and I hope to be able to greet you again at our next symposium.

Permit me to now introduce the head table. From left to right is Frank Cihak, the APTA Executive Director in charge of engineering and development; followed by Ron Kangas, Division Chief in the Urban Mass Transportation Administration; Antoine Lombart, who is Mr. Cihak's equivalent in Europe for the European APTA; and Helen Edge, of the Rail Progress Institute, representing the rail manufacturing association; Dave Wagner our keynote speaker. I will be introducing him in a few minutes.

Peter Benjamin, whom I will now introduce, is the Associate Administrator for Technical Assistance at UMTA. He's the man in charge of the Urban Mass Transportation Technical Assistance Program. I'd like to let him tell you about what UMTA is doing.

PETER BENJAMIN:

Thank you, Steve. As I was coming here this morning, I reflected that it was about this time of year in 1936 that the American Transit Assocation first unveiled the President's Commission Car, the new trolley which is even today, the standard in the light rail industry. One of the most important things about that new trolley was not the fact that it had wider doors to make it easier to board, and not the fact that it looked a little bit more streamlined and modern, but the fact that it had a brand new propulsion system which increased its efficiency and its ability to accelerate rather dramatically. It revolutionized the rail industry and the trolley industry of that time. Just a few years earlier, gasoline engines on buses had been replaced by diesel engines and the bus started to replace the trolley. So it was just about the same time that this new advance in trolley technology started to be overtaken by another mode. I also reflected on the fact that since that time, there have been no really dramatic improvements in the propulsion of our transit system; yet today we are on the threshold of a number of improvements and I'm very pleased to be part of a program focusing on ways that we can really improve our transit systems. We are focusing far more strongly on the propulsion elements than we have in 40 or 50 years. We're looking at electric power and new forms of electric power, particularly in buses. We are starting to look at such exotic technologies as fuel cells in buses, and to think about how they might be used in moving our people around our city streets. We have a project on magnetic power induction. We're looking at different ways of transferring electric power into buses.

As Steve mentioned in the rail cars we are looking at alternating current propulsion and at more efficient ways of moving our rail cars around. We have already started the introduction of advanced electronic control systems into rail cars. These are the types of changes that haven't happened in almost half a century and they make this conference very, very important.

Steve asked me to present an overview of what the technical assistance program was all about. What is it that we and the Urban Mass Transportation Administration are doing in the area of technical assistance? Let me give you a very brief summary of our activities.

We spend about $50 or $60 million a year on a very broad range of activities including management, financing, safety, planning techniques, maintenance, construction, and information systems. Advanced propulsion systems are an important part of that. In the bus and rail area we spend about $15 million per year. A very large portion of what is spent in those areas is focused on subsystems, particularly on the propulsion portion. Our purpose is to identify the needs of the public transportation industry today and to work with the industry to have a better understanding of where to focus those resources and efforts, to pursue a series of projects that address those needs as they've been identified and to work with the industry as closely as possible to assure that what we do is what the industry really thinks it needs, and finally, to get the products out. In order to get those products out not only do we have demonstrations, and get equipment out and running but we hold a large number of conferences. We probably hold one conference or workshop every week, most of them not quite as big as this one, most of them not with an international audience, but we have some sort of conference or workshop every week. Also, almost every week we have training sessions for the transit industry so our focus is upon developing and getting the results to the people who really need it. To bring together those people and have them all talk with one another is one of our major goals and it certainly is the one that we have for this particular symposium.

As we look at the propulsion activities that we're carrying out there are a couple of assumptions basic to our program. One is that the United States transit industry today is in financial trouble. It has to find ways to cut costs, and cut costs dramatically. We are looking for systems that are more reliable, easier to maintain and have lower energy costs. It is within those objectives that we are looking for new propulsion technologies. We also believe, at least some of us believe, that the cost of petroleum will continue to go up and that the availability of petroleum for powering buses may be questionable. As a result, we're looking for alternative means for moving buses and we're looking at fuels such as methanol and electricity as mechanisms for powering buses.

We are also looking at the large number of new rail transit systems that are on the verge of initiation throughout the United States. We want those systems to come into being with today's technology, not with technology that's fifty or thirty or even twenty years old, so one of our aims in discussions over the next few days is to hear about what we can introduce in new rail systems and in new buses over the next few years.

The results of this conference will be reported, as are the results of all of our conferences and all of our work. Everything we do has a final report associated with it. In almost every area of our work we hold a series of meetings to give the results. We do that through the various groups that are participating in this conference, through special workshops and through special reports. We hope that you will stay in touch with us to give us information so that we can pass it on to others. We hope that you will participate heavily in this conference and give your own ideas and ask good questions so that we will understand better what we need to do in the coming years. We invite you to attend more of our workshops and get some of those reports that we turn out so that we can be of more assistance to you and the entire transit industry. I hope you enjoy our conference and that this symposium is a very valuable experience for you; I know it will be for us. Thank you.

MR. BARSONY:

Thank you, Peter. The next speaker is our Maryland Urban Mass Transportation Administrator and General Manager of the Metro System, David Wagner.

KEYNOTE ADDRESS: PRACTICAL USES OF RAPID TRANSIT TECHNOLOGY

David A. Wagner
Baltimore Mass Transit Administration

Good morning, ladies and gentlemen, and welcome to the city of Baltimore.

It seems most fitting that our city was chosen for the site of Transpac '84 -- with the focus on innovation and breaking new ground in transit, you have also come to a city which is innovative and has broken new ground in urban development.

The Baltimore Region is on the move, with signs of growth everywhere. In the city, the Charles Center area and the dynamic Inner Harbor are the dominant symbols of a new downtown, and are changing the face of the city. Beyond the urban landscape, the suburbs' town centers thrive, and employment centers are expanding. The emergence of new residential communities, shopping, educational and medical facilities heralds growth and development throughout the region.

Let me talk for a moment about what we have here: Baltimore was founded in 1729 along the shores of the Inner Harbor, which quickly became a major center of maritime commerce. The Chesapeake Bay port is still the single largest economic factor in the region.

Our city has recently been called a "Renaissance City" because much of it is being renovated and reborn.

The revitalization of downtown Baltimore began in 1959, with the development of the prize-winning Charles Center urban renewal project. Charles Center, located just to the north of this hotel, consists of a unified complex of office buildings, apartments, hotels, and a theater connected by pedestrian plazas, walkways and retail shops.

With a total development cost of $180 million, the 33-acre project is nearly complete. Fifteen major buildings are in use.

As a result of the success of Charles Center, the city undertook the redevelopment of 240 acres, surrounding the historic Inner Harbor. A 30-year program for redevelopment of this huge area was unveiled in 1964. Stretching to the south and east of Charles Center, the Inner Harbor projects are adding residential, social and cultural facilities as well as major hotel and office buildings. The new structures are solidifying Baltimore's reputation as an urban center of distinction, charm and vitality.

A basic concept of the Inner Harbor plan is to return the shoreline to public use. Prime consideration has been given to providing waterfront land for recreational use. Included are:

The National Aquarium
The World Trade Center
Harborplace
This Hyatt Regency Hotel
The Convention Center
The Maryland Science Center
Both new and restored residential units and open space and parks.

- There are plans in the works now which will add $550 million in additional investment, making a total investment of about $2 billion.
- The city's real estate tax revenues have increased by almost $11 million a year.
- The number of people in the business district -- living, working and visiting -- has tripled in the last 20 years.
- The Charles Center and Inner Harbor projects have won 22 major awards for excellence in design and execution.
- Baltimore's downtown redevelopment program has become world famous. In one year alone, the management office was visited by 4,000 Baltimoreans and visitors from all over the world.

A major impetus to all this development was the guarantee of quality accessibility by highway and by our new rapid transit system. The new Baltimore Metro, which opened last November, is also a cornerstone of the renewal of the old downtown Financial District, now under way.

Growth is not new to Baltimore. The city dates from colonial times; only the pace is different -- more immediate, more demanding, more accelerated. As is true in other metropolitan areas, growth is accompanied by pressing public needs for mobility.

The Mass Transit Administration operates a bus and rail system of more than 900 vehicles, including van and taxicab service for the handicapped, as well as extensive park 'n' ride express service. The MTA is also responsible for the design and construction of future segments of the Baltimore Metro. As with any new transit undertaking, the Baltimore Metro has used some new ideas. In the United States, each new rail system historically has been built on technology developed by the systems which have come before. As the BART system in San Francisco passed technology on to Washington's Metro system, Washington passed on ideas and equipment to Atlanta's MARTA. MARTA in turn provided ideas for the next generation -- Baltimore and Miami. And there are those who will be looking to us.

However, it must be recognized that someone must be out front in the research and development area. The transit system which tries the new, the cutting edge, makes the job of those to follow much, much easier. But that first system to use an idea can also end up paying a heavy price -- both financially and also in public opinion.

Here in Baltimore, we have been a bit more conservative in embracing new rail transit technology. For several reasons, we do not have the very newest, the least tested, the most exciting. Those reasons are largely political: funding for new rail systems in this country is severely constrained -- much more so now than just a few years ago. Also, the Baltimore Metro has been politically sensitive since the very beginning. Because of the fact that the project was approved by the state legislature by a one-vote margin, and because of some very vocal opposition, it was imperative that every part of our system work well. In short, we could not afford to be on the cutting edge of technology.

Of course, this in no way denigrates those systems which have been more innovative than we have. They have paved the way for us. And as we move forward in building other segments of our system, we will look at future innovations in transit.

The development of the Baltimore Metro did include an interesting project pertaining to tunnel liners. A $400,000 grant was awarded to the MTA to cover the instrumentation and monitoring of precast concrete tunnel liners on one of our tunnels. The $93,000 cost differential between the concrete liners and the regularly used steel liners was funded 100 percent by an UMTA R&D grant. The monitoring program compared the cost and technical performance of the two types of liners.

Although not a new technique to those Europeans among us today, this was a useful project for someone in the U.S. to study the benefits and/or drawbacks. This is an idea which can be passed on to other transit systems.

We also were able to handle our construction insurance for the Metro project in a new way: in conjunction with UMTA, the MTA chose wrap-up insurance, at a cost of 6 percent of the project value, over conventional insurance, predicted to be 10 percent of the project value. Wrap-up is a method of providing insurance for all contracting parties through a centralized marketing and administrative facility known as the insurance administrator. This plan was a great success, and we are using it again on our Section B construction.

As I mentioned, we are not only a rail system. The vast majority of passengers provided service by the MTA ride on buses. We have also participated in several research ventures with UMTA on the bus front. We believe that any time you are dealing with new technology, it is necessary to investigate that technology in as controlled an environment as possible.

One of our more interesting R&D ventures was the turbine bus project. Begun in 1979, we ran four buses equipped with gas turbines on inner city transit lines. In conjunction with UMTA and the U.S. Department of Energy, the carefully controlled project's predicted benefits included less noise, less pollution, less vibration, improved vehicle performance and reduced weight.

We did find advantages to the turbine buses: they had an extremely fast startup, and a quiet ride -- on the inside. However, from the outside the buses had a noisy whine. The turbine was too strong for the inner city routes, and there were extreme heat problems. Transmissions burned out. We even melted the heat-resistant vinyl panel on the side of the buses. After three years, we concluded that some R&D projects find that the original idea is not a success.

Our newest R&D project is just getting off the ground. We have received a $130,000 demonstration grant -- $104,000 from the federal government -- to install automatic pass readers on 50 of our buses. This is a brand new project: when the decision was made to proceed, the machine did not yet exist. A mockup has been made by the French firm of Creuzet.

Basically, the machine will be mounted near the farebox on our buses and is expected to automatically read various passes and transfers, the fare paid, and whether a pass is valid. It is estimated that the entire process will take about one second per passenger.

No one else in the U.S. has tested such equipment, and the major concern is whether the pass readers can stand up to being mounted on a moving vehicle. If the test is successful, we would like to install them on all of our buses by 1987.

The transit industry is always looking for ways to improve, especially in the areas of maintenance and operating costs. Research and Development is one of the means by which that improvement will come, and we look forward to participating in upcoming R&D projects.

Thank you.

INNOVATIONS IN TRANSIT TECHNOLOGY

CHAIRMAN:
GEORGE PASTOR
SPEAKERS:
RAINER GOETZ
International Market
JOHN M. MEISTER
FRANK J. CIHAK
Domestic Operations
ANTOINE LOMBART
International Operations

RON KANGAS:

Leading this discussion and session is an individual who needs very little introduction to this audience. He has been a powerful and articulate moving force in the transportation field for well over a decade -- George Pastor. I first met George in 1971 when I came to work for him at the Transportation Systems Center in Cambridge. After a few years, George went to Washington, where he became the Associate Administrator for Research and Development at UMTA. In 1980 he moved to his current position, the President of UTDC USA, where he markets and delivers all of the UTDC products in the United States. George also has a prior life as most of us do. He spent about 15 years in the aerospace and defense establishment working with manned space craft centers and specifically working for Philco Ford and the Lockheed Corporation. George also holds a Bachelor of Science degree in electrical engineering from Columbia University and a Master's degree in electrical engineering from the University of Southern California. George Pastor.

MR. PASTOR:

Thank you very, very much. I feel both honored and somewhat nostalgic to be back here with you. As a matter of fact, I remember the first conference that Steve alluded to, which was four (4) years ago at the Four Seasons in Washington and I guess Transpac joined the leap year activities in the U.S., winter and summer Olympics, presidential elections and Transpac to be held every four (4) years.

I'll give you just a very brief commercial and I hope I can put it in an admissible context. UTDC, my parent company, is a company today which offers a product line from people movers to street cars, subway cars, commuter rail cars, and we're even thinking about inner city rail cars. So, we have made a fantastic commitment to the big skyway transit market for the rest of this century. We believe in it.

Now, in juxtaposition with that, let me cite something that I heard many years ago from a supplier which characterizes the transit market. I wish I knew who said it, but I don't remember, because he said that those who finance transit never select or buy the product. Those who buy and select the product never pay for it. Those who pay for it never ride it. Those who ride it never select, buy or pay for the product. I think it's a very apt characterization of the transit market and it's very difficult for us indeed to adjust. It's a long way of saying it's a politically dominated public market to which you can't necessarily apply the rules of the commercial marketplace.

In this market, as it was alluded earlier, new technology introduction is a political risk, not a profit risk, not a bottom line P&L problem, but an embarrassment, a political "heads-can-be-rolling-and-we'd-better-recognize-it". I think it is in that spirit that after six (6) years as an associate administrator, I look back on my accomplishments and in retrospect I believe the greatest accomplishment for which I can claim fame is that one sentence in the Urban Mass Transportation Administration enabling legislation known as 3(2)(1)(C) which says, "Capital grant funds may and shall be used for the introduction of new technology." I think that accomplishment, if it's maintained and if it will be continually funded, is probably larger than transbus, Morgantown Peoplemover, or even the DPM program.

Now, in trying to set the stage for innovations in transit I wanted to throw out just a few thoughts. Some of them are pretty old, some of them are new to stimulate some debate, questions to the panelists and so on. We are now in an age in which we talk about our smokestack industries retrenching. We are searching and developing a new high tech industry. Flying here on the plane I read a commercial by Hertz introducing the new Continental Mark VII, and it talks about more electronics in the Mark VII than in any automobile before. Engines are controlled by mini computers, fuel consumption is controlled by electronics, the dashboards of our cars have electronic display devices. I think that after the agonies of the three (3) years recession in the automotive industry, we are discovering that by having fallen behind in technology we almost lost the most basic industry in this country.

Now, put this in juxtaposition with our transit industry. Very understandably because of the political dominations, they are tremendously afraid of technical innovations. We put in a bid for a light rail vehicle. We have to demonstrate for every subsystem how many hundreds of those subsystems have been used for how many decades at various locations before we are allowed to bid that particular subsystem. Here are the contradictions of the environment under which we labor. Nevertheless, just as the automotive industry recognizes today that new technology is potentially their life blood, I want to repeat what I said in the very first speech that I made as Associate Administrator in front of TRB. Don't tell me that for the rest of the 20th century new technology cannot beneficially contribute to transit equipment when we've been using the technologies that were developed over the last century. There is a rule for new technology and I think it is emerging. It is emerging as we introduce new technology systems in this country in Miami and in Detroit. We are introducing the people mover. In France, the first fully automated and unmanned metro has been in operation since April. In Vancouver we have been running five (5) years in a demonstration mode. These systems will open up. In the same way conventional transit will introduce new propulsion techniques, new automatic control techniques will make transit economically acceptable, viable to continue to perform that service.

I would like to introduce our speakers who will add to this and set the stage. Unfortunately, Jean Marie Aubriot could not join us. Jean Marie didn't make his flight back from Europe. I asked an old friend, Rainer Goetz, who was at one time the one-man UMTA in Germany and for the past four (4) years running as President of SNV, which stands for Studiengesellschaft Nahverkehr which is urban transit in Germany, to address a few words about how he sees the international market. Rainer, please.

MR. GOETZ:

Thank you, George. First, there's the international market and then transit innovations. George already mentioned the new systems under development and under construction in some of the countries. I think we have to divide the international market into some market shares, countrywise. We do have the countries, the eastern region, and there normally we don't sell too much from the western countries. The second market share is the developed countries. The developed countries are, I think, Great Britain, France, Germany, Japan and Canada just in sight of transit industries developed. There are other transits to assist us and main developers of transit systems and here we have somewhat more or less closed markets. It's normally the French, German or English industry that supplies the systems and I can add to George's words that we believe in the transit market. We in Germany still believe in public transportation and so this still is a strong market in our own country but this market is not for other people as it is in France and England and Japan, for instance. So, we do have two (2) other market shares. One of them is the U.S. The U.S. is a foreign market from the sight of these development countries. Then there is the big third share and that of developing countries. It is in these developing countries the main competition takes place at the moment, as far as I see it, and now we do have other market shares from the sight of the innovations.

What is innovation? George already mentioned conventional rail wheels. We do have innovations in conventional rail wheels and most of this conference will focus on this innovation so I don't have to make comments on that.

The second point is the group rapid transit and the personal rapid transit systems and as we mentioned the people mover business. This is the real innovation from the basis to the top and I see this as a somewhat limited market in comparison with the overall transit market but I think it will grow in the future and come step by step from the single use systems like downtown people movers, like airport people movers and special places people movers, which have limited extensions.

But I think there is a third group of rapid transit systems and that is the developing conventional bus system. The bus system is looked upon and has been looked upon in the past as a system where a bus runs on a line and there is to be a sign pole at the stops. That this is as far as we in Germany have now developed this system is only part of the truth. You can make out of the bus system a rail system that has all of the components you have with rail transit and in this direction we developed a concept that can be put into realization step by step. You can start with a small part of tunneling to very extensive tunneling. Then at the beginning, you have the opportunity to let the buses run through this tunnel and then go out all over the place and put another piece of tunnel to this. We do have this step by step approach too in the rail systems area, with the light rail system where you can start with the first tunnel and a small portion and go in operation with a bigger network. That's peculiar to our country, I think. We do have a step by step approach with the so-called S-Bahn System. We stepped up in Munich and with just a small part of 4 km of tunnel we created a whole network of rail transit of about 400 km mainly on existing track for heavy rail.

So, these are the market shares. If you just make your metros out of this matrix you will have twelve (12) fields. I have remarks on three other points. One of these is competition. In the international field competition grows. More and more countries are in the position to supply conventional rail systems and conventional buses so the market becomes very tight. For instance, in Singapore, as I remember, there were hundreds of bids on parts of the whole contract and this is a sign of new competition from very, very many people and this shows too that the market is now really international, not just some big industry that can afford to go abroad and give out bids there. A multitude of industries can do this now.

The second point is financing. Financing becomes, especially in the developing countries, more and more difficult because of the economic situations there, and so the techniques are not the only point. The point is if you go there as an industry out for bids you have to bring the financing and the backing you get from your government and from your banks. It is the main thing in this competition.

The third thing I would say is coming back to the start, and I have some closing remarks on innovations. I believe in innovation and think we have to do a lot there, especially in developing countries. This is our only chance in the long run to compete with all of the other competitors. Especially for high technology and high price countries, you can only compete in this field if you bring new technology, if you bring advanced technology. And the second thing is, if you then bring this new technology you are even more trustworthy on the conventional technology. If somebody can make a system run with the reliability of even 99.99% on a new innovative system, it is believed that he can build a very good conventional system. So I think we just have to go further with innovations as developed countries and then we can stay on the international market. If we fail to do this and make it very simple in our own country, then we will not have the headway we need for the other countries to come up now. Thank you.

MR. PASTOR:

I just want to add that you can include the United States among the underdeveloped countries when it comes to bringing your own financing package.

Our next speaker is John Meister. Unfortunately, John Geikler couldn't attend today, but Mr. Meister is an old hand at Westinghouse and I'm sure he can convey to us their views about innovation and transit technology. John Meister has a B.S. in electrical engineering from Carnegie-Mellon University. He has been with Westinghouse since 1969. He was a project manager in the Washington Metro Program starting in '72. In '76 he became Division Project Sales Manager. In '79 he became Marketing Manager for Transportation Division and in 1981 he assumed his present position as Manager of Engineering. I'm glad to welcome John Meister.

MR. MEISTER:

Thank you, George. Good morning. As George said I am substituting for Jack Geikler, our General Manager, because he is visiting the Far East at the request of the U.S. Department of Commerce. Jack's comments are in the proceedings and I encourage you to read them. As he usually does with me, Jack has emphasized technology development, not for its own sake, but for what it will do to reduce cost and improve reliability and quality for our customers, some of the same things Dave Wagner already talked about. I believe his comments are well worth reading.

If you will permit me I would like to stray slightly from the theme of this session, "Innovations and Transit Technology" and discuss briefly with you innovation in a more general way, and hopefully give you something to think about besides trolley cars and buses. Experts in our government have identified four (4) forces working today interactively that will continuously restructure the United States and world economies over this decade and beyond. The first of these is of particular interest here in the United States. It is an adverse relationship between our former tax laws and chronic inflation and it has eroded much of the assets of smokestack America over the last 20 years. The second force is technology explosion. About 90% of everything we know today in the sciences has been developed only in the last 30 years. This explosion in technology has led to early obsolescence of facilities, equipment and processes. The third force is the targeted industry strategy that some nations have adopted so effectively and that every nation in the world must copy sooner or later in order to survive in our global economy. And finally, the fourth force. As less developed countries emerge into the world markets they will take advantage of their large supply of natural resources and their inexpensive labor. This will enable these less developed countries to gain a significant market share at the expense of the USA and other developed countries.

There are many interesting things to analyze about all of these trends but since this is a technology conference I will focus my comments only on the second course, the technology explosion. This slide, which I have borrowed from Bruce Marafield of the Department of Commerce, supports my earlier statement that 90% of the world's current scientific knowledge has been generated in the last 30 years. Historians view this as a hallmark event which has no precedent in the history of mankind; however, the really exciting thing about this revolution is the prospect that we will double our current knowledge base again in just another 10-15 years. Unfortunately for Americans most of that knowledge expansion will occur outside of the United States. The Commerce Department estimates that the United States through 1975 generated 75% of the world's technology with less than 5% of the world's population but in the last 10 years our share of development technology dropped to 50% and in another decade it will only be a third. The reason for the dramatic decline is not because the U.S. is generating less technology; in fact, we will be generating a lot more. It is rather because the other 95% of the world's population is getting into the act and generating even more than we are. Every nation sees technology development as the essential ingredient for improvement in the quality of life and they intend to participate. Just think what one billion people in the People's Republic of China could do if they ever got the leading edge of technology.

Let's talk a little bit about the innovation process that translates this scientific knowledge into something useful. We can characterize it as an innovation pipeline that starts with an idea and proceeds through technical feasibility checks in the laboratory through product development stages through a pilot plant or prototype stage, through semicommercial or interim manufacturing and finally into full scale operation. This entire innovation pipeline is a 7-10 year process for major developments. Interestingly enough this development flow and time frame pretty much parallels our industry.

In the United States the Commerce Department estimates U.S. industry puts about $10 billion a year into the innovation, invention and idea generation stage. This is the fundamental pool of knowledge that the Commerce Department estimates is about ten times more than the rest of the world; however, the next three (3) stages in the pipeline account for 90% of the cost and risk in technology development. This is where in our industry, the transit industry, we need cooperation among user transit authorities, federal and local governments and suppliers. George already mentioned the U.S. Government 3(2)(1)(C) program where DOT will sponsor the demonstration of a supplier's new designs on transit authority properties which is an excellent start towards cooperative effort. I really didn't know George was the father of that.

The UMTA sponsored AC Propulsion Development Program that you will hear about on Wednesday is another worthwhile example of essential cooperation among transit authorities, governments and suppliers. I applaud the efforts of all involved in these programs and hope that this type of cooperative effort will continue. If it does not that fundamental pool of new technology in our industry will be exported overseas to countries that are willing to assume the cost and risk of translation into commercial operation. Such countries will develop our ideas and then resell them into the United States. It has already happened in other industries in the United States including steel, radio, auto, video equipment and now it's happening in the latest technology 64-K memory chips. It can and is starting to happen in the transit industry.

Let me now explore for a few minutes some growth areas in the current technology explosion. I wish I had time and frankly, the background, to go into all of them in depth. Energy, biochemistry and electronics. Explosive growth is occuring in the material sciences, in engineering plastics and composites and its super alloys. Graphite fiber reinforced epoxies are stronger than steel but lighter than aluminum. They also don't stress fatigue or corrode. Soon they will be cheaper than steel and will replace steel in many applications including automobiles, airplanes and appliances. They're going to have a major impact on the materials business. As an example, at Westinghouse we are looking at composites for use on our people movers and graphite fibers for use of traction motors.

Another key activity area in material science is ceramics and laminates. As some of you might know, the Japanese have a ceramic engine running in the streets of Tokyo. It operates around 1200C. and has no cooling system. It is about a third lighter and a third more efficient than U.S. engines. Of course, it is based on work in ceramics and laminates performed earlier in the United States and is another example of U.S. technology ideas translated into reality by someone else. This engine could have quite an impact on our automobile business in a few years. It is only a typical example of what is happening.

In energy the experts at Westinghouse see our economy relying mostly on natural gas and electricity by the year 2000. We have enormous quantities of natural gas in the United States. Just a few explored areas in the Rockies and the Appalachian Mountains have revealed enough energy to fuel the entire United States for 50 years. In addition, the oil production situation worldwide has stabilized. The Mexicans believe they have more than twice the oil and gas than all of the

Middle East. The South China Sea may also have that much. In general, there is an incredible amount of drilling going on worldwide which is continually discovering new petroleum reserves. This is important because every underdeveloped nation in the world sees petroleum as the cash flow generator which will enable them to buy our technology. The natural gas and petroleum reserve situation means less concern over the price and availability of energy in the next few decades, barring some catastrophic interruption of supply such as an all out war in the Mideast. Then in about 50 years, again according to the experts at Westinghouse, fusion technology will be commercially available which should provide a 'permanent solution' energy supply.

Biochemistry is another important area of technology advancement. Genetic engineering has been talked about a great deal, especially for its commercial advantage to agriculture; however, there will be certain other advantages applicable to the human situation as well, including the elimination of many genetic diseases like diabetes. In addition, you can be sure that this science will develop to the point that cancer will be defeated. As this technology growth area continues to develop, our life spans will be extended maybe as much as 50 years. Think of the profound effect in our world of middle age being 65 instead of 40.

And finally, how could a representative of the Westinghouse Electric Corporation make a speech without discussing electronics? Electronics are and will continue to be pervasive in our lives. Everything that moves will have a microprocessor in it. Electronic mail will interconnect the world. Right now, at Westinghouse, I can communicate electronically with other Westinghouse employees from my home at any hour of the day or night. Go anyplace, our company has an office in the world. Communication tools like electronic mail will have a tremendous impact on education as well as business. The new frontier of education will start at age 22 and will be a lifelong re-skilling that will be necessary to prevent early obsolescence. Other tools like video disks and interactive computer terminals open even more opportunities in the education field. We are using these tools at our Baltimore Defense Center and I could tell you the increase productivity and the quality of our training programs is enormous. Initial statistics gathered by HEW support our findings and show at least a 100% greater rate of learning and significantly improved quality of learning in our schools that use these systems. These advancements will allow us to efficiently and effectively recycle our people who will be displaced from jobs in the declining industries. There will be many, many more jobs than there are people in the USA, but this skill, mismatch, has got to be addressed. Growth and technology will provide us with the powerful tools to do just that. Education will become a life-long task but we'll be able to perform that task in our living room.

And robotics. It's just now starting to make its presence felt in our society. To give you an idea of the role it can play in the industrial world I would like to relate to you a recent plant tour I made at the Ford Engine Plant in Mexico. I followed an engine block and a crank shaft through their entire production operation, about a half mile and neither one was touched by hands until they reached the final assembly area. Even after final assembly the units went back onto an automated line for testing and shipment. It was truly incredible. Of the total value of that engine, less than 5% was labor. When I got home I explained what I saw to my wife. She showed me an article that had been published in the Pittsburgh Press that same week quoting experts at Westinghouse that the same thing I had seen in Mexico would be commonplace in our homes in less than 15 years. All I know is the sooner that robot can wallpaper the better I'll be.

I've just touched the tip of the iceberg regarding the potential for growth and use of electronics. There are thousands of new products based on advanced electronics technology that will be introduced in the next decade which will change our lives. We have to be ready to accept the challenge of this rapidly changing technology environment.

In summary, there are four (4) major world forces that will continuously restructure the U.S. and world economies over this decade. Our challenge then is to manage this change. Management by definition will become the management of change. We in the transit industry as well as the entire U.S. manufacturing industry must structure to manage this change. This will require cooperation among customers, suppliers and the government starting now. Thank you.

MR. PASTOR:

Thank you very much. It was quite a thought-provoking presentation. If we now solve the problem of what to do with people who get replaced by technology we'll have it all wrapped up.

Our next speaker, and we're going to do a little bit of a switch, is Frank Cihak, who will talk about domestic operations. Frank is the Executive Director of APTA and he stepped into the very big pair of shoes that were vacated by Bob Coultas, and has done a very competent and able job. Frank has a Bachelor's degree in Mechanical Engineering from the University of Illinois. He has 15 years of experience in transit, mostly in design, procurement, and maintenance. He is a graduate of the Chicago Transit Authority, which I believe runs one of the best industry training facilities in the country. He was Chief Equipment Engineer. In 1977 he joined APTA and is now Executive Director for Technical Services. Frank.

MR. CIHAK:

I'd like to talk to you about the domestic operations, scope and magnitude, some of the issues that we face, and then lastly, some areas calling for technology. I'm sure in the next few days you'll hear a lot more about these areas calling for technology.

Magnitude and scope of public transit operations in the USA as of the beginning of 1983, the last year when full statistics were available, shows that this industry is a pretty good sized one. It's just under a $4 billion a year industry in terms of revenues and employs roughly 200,000 people. Now, that's in the direct provision of transit service; on the supply side are the manufacturers or other employees, of course, depending on the business. This transit service provided 58 billion passenger miles during that year and it was provided by the two (2) major elements, the bus fleet which was further subdivided into motor buses and trolley buses. There are 62,114 motor buses in this country and the average age of that fleet is about 6.8 years. The trolley buses being much fewer, 823, operated by five (5) transit systems have an average age of about the same, 8.2 years. Total bus operation therefore is equal to 62,937 buses which accumulated 1.682 billion miles annually. This number of buses carried 21 billion passenger miles.

The second portion of the industry is the rail fleet. In this particular case I will speak of light rail and heavy rail cars and I will omit the commuter service. In light rail, there are 1,016 cars operated by 11 transit systems. The average age of that fleet is much, much greater, 22.8 years. In heavy rails cars, there are 9,697 operated now by 10 transit systems and the average age of that fleet is slightly better, 19 years. So as you can see we have an aging fleet on the rail side.

There are issues that we might describe in new technology related to transit. First of all, it was stated already that no one in this business is particularly interested in technology for its own sake. The people that operate it certainly aren't. The people that ride on it definitely are not. Bob Johnson, the former General Manager of PATCO once described his transit cars as "people boxes" and that's my observation; the passengers really don't care what's underneath it as long as it gets them where they want to go. This interest is really in the results of the service provided. People are interested in dependable service, provided at a reasonable cost. To be successful, new technology must satisfy several transit system requirements, the first of which is safety. Safety is foremost in this business and must not be compromised to any extent by new technology. Second are reliability and it's attributes: availability, maintainability and dependability. The people don't care what's providing their propulsion, they're interested only in the results and that means getting where they want to go on time. Any new technology certainly must satisfy environmental aspects, must not be noisy, must not provide excessive vibration, and must not have any unusual pollution source. Certainly, it should look nice, it should not interfere with people's television sets, pacemakers or whatever other electronic device they may have. Fourth, life cycle cost factors must be considered and basically, the system must provide its service at a reasonable cost. And last, the performance of any new system must have been demonstrated in an environment such that the purchaser has sufficient confidence that it will work in his environment.

These requirements may seem stringent and they certainly are, but they must be addressed before research money or other funds can be expended to procure equipment. Technology must offer positive cost benefits in order to be utilized by transit systems. The financial status of transit systems as was described earlier, permits little or no margin for error in the development of equipment. Therefore, cooperation between government, industry and transit system management and application and utilization of advanced technology to enhance the operation and maintenance of transit systems is essential to progress.

Now what are some specific areas we might call out? These are not particularly earth shaking ones; they're rather mundane. Propulsion system designs basically must do two (2) things in the future: they must require less utilization of resources, that is, skilled labor, time out of service or the need for expensive hardware and second, they should ideally achieve reductions in fuel or energy consumption when they are operated. Another area we think is coming up very greatly is the use of diagnostic equipment or self-check equipment for both bus and rail. This equipment is low cost, readily affordable or built-in, easily understood and accurate. It can provide a means of accurately troubleshooting and validating proper performance of vehicles in subsystems and, as would all test equipment, must not have any capability to adversely affect the functions of the devices being examined. Another item we see is signaling and control systems. There is, of course, a greatly proliferating use of microprocessors. Accordingly, standards for both hardware and software of these devices must be established to assure that such items address and are compatible with the needs of transit systems. Again, in this context safety is important. Lastly, you might consider the availability in the long term of electronic parts. We foresee that with the greatly increasing pace of technology there's a corresponding decrease in the life of equipment, where in the past the transit system could probably manufacture in its own shops most of the equipment it needed to maintain equipment. We do not see this in the future and therefore, the availability of parts to operate systems must be considered, or else we must have some other scheme such as a major midlife redesign or re-equipping of propulsion equipment. So, in all of these, transit system management is quite aware of the pace of technology and they are, I believe, very careful to adopt systems that do provide service without undue risk.

Transit system management, in fulfilling it' responsibilities to its patrons, must demonstrate their merits in a transit environment as far as technological advances. Such demonstrations must not only occur first in the laboratory, second on a test track, but also in a closely monitored environment in revenue service on a transit system.

These are just some of the ideas that we might want to think about during the conference. I would also like to invite the APTA members in the audience to be back here on June 12th, 13th and 14th when we have your Rapid Transit conference. There will be approximately 1,000 people here, probably 250 technical presentations being made in about 40 different sessions. Ted Gordon, who is in the audience, will answer any questions regarding that conference. We hope to see you there. Thank you.

MR. PASTOR:

Frank, thank you. Now, as you all know the city of Brussels gave a new word, over a decade ago, to transit and that new word was "pre-metro". Now the city of Brussels gives us M. Antoine Lombart who is Operations Manager at Brussels' Public Transport Company. He's a member of the UITP. He is also a member of Transport Consult. He is Vice President of the Chamber of Commerce in the city Brussels and he is an Operating Officer, I believe, in the Commission for the Belgian Union of Public Transport. So, nobody could be better qualified than Monsieur Lombart to give us a little bit about international and foreign operations. I welcome him to this session.

MR. LOMBART:

Mr. Chairman, ladies and gentlemen, dear colleagues, good morning. Mr. Andre Jacobs, General Secretary of the International Union of Public Transport, in short UITP, has asked me to represent the Union on this symposium. Just as you have heard I am Traffic Manager of the Brussels Public Transport Company in Belgium and full member of the UITP and its Metro Rail Committee. This committee existed more than 15 years, organizes two (2) meetings each year and is composed of the leaders of the most important networks in the world. This country is represented by the networks of New York, Atlanta, Chicago and San Francisco. Each member of the Commission informs its colleagues of the results of research and obtained results during the last six months. During this work session a lot of information is transmitted and commented upon. All different types of subjects are analyzed -- advertisements, new construction methods of tunneling, use of new materials and projects. In operations, saving of energy, smaller maintenance costs, marketing aspects, struggle against costs. In the view of the passenger, there are the availability of the service, better commercial speed, better information and assistance to the passenger, protection against fire, vandalism, terrorism. The number of subjects increase each year. The Metro Committee had decided two (2) years ago to create different sub-committees on operation, rolling stock, fixed installations like track, power supply, stations, depots, workshops and buildings, finance and marketing. Other committees work in the field of best construction and best maintenance and propulsion, light rail operation, and fare policy. It is not possible in a general presentation and in a few minutes to give a total view of all the research and applications of new technology. I can, nevertheless, evoke the latest results and ideas in this way. There has been an important extension and progress of the shell method in construction of tunnels. A large number of decision makers look forward in this newly-adapted technology. The decision is taken in view of reducing, to a tolerable minimum, the trouble for residents, local trade, traffic and general environment which is not possible with surface construction methods.

The pipe jacking, a new horizontal tube crushing method that permits the construction of the roof of the tunnel just under the street level. The tubes are guided by a laser ray. There has been steady construction and testings of a lot of B-mode vehicles. B-mode trolley-buses moved by electricity or by a small diesel engine. The conception in Germany of a new special metro car with a water tank and sprinklers in the roof for immediate intervention by the first fire detection. A full automatic system in Lille, a city in

France; the system named VAL, Vagal Automatic Lieje, started with a success in operations last year without a person on board. It can be compared with the original high capacity lift. The platforms in the stations are provided with doors parallel with the track so that the waiting conditions for the passengers are maximized and the danger for accidents minimized. The central management of the traffic, and in more and more cities a total cooperation with the local authorities, is required in this case. The conception of a driving simulator permits economy in traffic costs. It eliminated mileage and gave the possibility to recycle frequently the drivers and train them continually. It is still dangerous and expensive to sophisticate too much public transport. All useless gadgets must be eliminated. Initially, in the Brussels heavy rail system, a camera and screen combination covered the boarding and alighting of passengers but poor visibility made it difficult for the driver to supervise these movements. The entire device was replaced by adjustable mirrors which give an excellent full-color image. To adapt the whole public transport system to the technology requires long study and progressive planning. The service of the public must be maintained in each case. We transport leaders have the duty, and it is one of the most important facts of our job, not to forget the human side. We transport more than 1 billion passengers aged between 6 and 80 every week in the world. In this approach the metro committee of the UITP has discussed the problem of the integration of handicapped persons to the public transport. The conclusion of this analysis was that the best solution was to organize service with special concept minibuses and to assure door-to-door service. It better answered the specific demands of this type of rider and did not penalize the normal passenger.

Mr. Chairman, ladies and gentlemen, this very quick and incomplete survey of the different tasks of the transport managers proves the importance of international meetings and symposiums. I am very glad to be here to listen to the different papers given in these two (2) days of meetings. I would like to inform you also that from 19 May to 24 May 1985 the UITP celebrates in Brussels, 100 years of existence. A very important exhibit is prepared on that occasion. You are all welcome to Brussels in 1985, and also before. Thank you for your attention and for the patience you have had to listen to my English. Thank you.

MR. PASTOR:

I hope that we have succeeded in at least setting the stage for the next two (2) days of deliberations here. If anybody has any questions for the panel members, please do so.

INNOVATIONS IN TRANSIT TECHNOLOGY: DOMESTIC MARKET

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INTRODUCTION

Over the last twenty years, several significant advancements have occurred in the technology applied to mass transit systems in the United States. Solid state chopper propulsion control, computer-based automatic train control, microprocessor-based logic control, and various forms of automated guideway transit are some of the most important.

Westinghouse is proud to have been a leader in advancing the state-of-the-art in these and other areas used in the transportation industry, both domestically and internationally. When the contract for the BART system was awarded to Westinghouse in 1969, it resulted in the development of a completely new form and generation of automatic train signalling equipment. This same technology has since been applied successfully at the Sao Paulo Metro in Brazil and at a number of rubber-tired People Mover systems throughout the United States and Great Britian.

Since BART and Sao Paulo, more than 1900 units of Westinghouse advanced chopper propulsion have been placed in revenue service or are on order for heavy and light rail applications and for the latest generation of electric trolley buses now in service at Vancouver, British Colombia.

But in spite of these and other developments, the domestic market for new transit technology has often been frustrating for the true state-of-the-art innovator. Moreover, the issues and needs surrounding transit operators today are changing the focus for future development away from revolutionary technology innovation to achieve higher system performance and toward evolutionary technology enhancement to achieve system quality improvement. Higher quality transit service measured by improved equipment reliability and lower life cycle costs must be the goal of technology innovation in the future for domestic transit systems.

This presentation will describe the forces impacting technology advancement in the U.S. market, the responses of suppliers to these forces in the form of improved products and services, the characteristics of the market that retard continued development, and a proposed approach for meeting the technology needs of domestic operators.

ISSUES AND CONCERNS

While concern for advancing the state-of-the-art of U.S. transit technology may have played a role in leading the developments of the last two decades, user properties in the U.S. are not generally concerned about showcasing new technologies or funding basic research to develop feature-laden equipment for their systems. Fears of increased cost and maintenance complexity from new, sophisticated technologies, even with the promise of higher system performance, have made many U.S. operators lukewarm at best toward technology innovation.

Instead, reducing cost and improving reliability are the chief concerns of the domestic transit community today. Declining operating subsidies from the Federal government and the limited availability of capital funding for modernization and expansion have forced transit operators to focus attention on meeting tougher financial goals and improving the operational efficiency of their systems. U.S. transit managers today are challenged more than ever before to enhance the reliability and availability of their systems, and their image as public servants. Ridership must increase to improve the worsening financial condition of domestic operators.

These concerns actually revolve around a single issue: quality. Improving the quality of equipment and services supplied to domestic transit systems is essential to increasing their on-time availability to the public, and reducing their total life cycle cost of ownership.

Improving quality means several things. It means that both suppliers and user customers will design, build, operate and maintain equipment the right way every time. That means having the skills, tools and training to do every job right the first time.

It also means applying advanced technology to transit applications in ways that help reduce human error, reduce cost and improve reliability and efficiency. To meet these goals, suppliers are re-focusing their investments toward improving the quality of the products and services they sell, because their user transit customers are demanding it.

APPLYING TECHNOLOGY FOR QUALITY

At Westinghouse, innovation and investment for quality improvement of both the products and services we provide and our design, manufacturing and management processes have become the keystone of our technology strategy. Let me highlight a few of our most important product and process technology development programs.

In the product area, a variety of refinements and enhancements are underway to expand the application of solid state devices into rail transit car propulsion equipment. Replacement of additional electro-mechanical switching devices with thyristor control devices in our latest generation of chopper propulsion control at SEPTA's light rail system in Philadelphia has enabled that equipment to achieve a phenomenal 2600 hours mean-time-between-failure since it was placed into service in 1982. Maintenance cost has also been reduced by eliminating electro-mechanical components.

Continuing advancements in applying microprocessors to logic control for transit car propulsion and signalling address quality improvement by allowing systems to operate more efficiently and flexibly. In addition to being highly reliable, microprocessors are easily programmable and operational changes can be made quickly by a simple change in system software.

Westinghouse is also participating in one of the last research and development programs to be funded through the Urban Mass Transportation Administration, the development of an AC drive propulsion system for transit application. AC drive has long been recognized for its potential to increase not only the performance of transit vehicles, but also their reliability while eliminating the maintenance costs associated with DC traction motors.

A less obvious but no less important area for quality improvement through technology is equipment packaging. We are paying more attention to designing car propulsion equipment, for example, into more easily maintained modules and components. At the same time, we want to design equipment packages for ease of manufacture, both to reduce cost and to eliminate the possibility of errors in the building process.

Improved diagnostic capability is another key to improved quality. New solid state enhancements for diagnostic equipment are reducing system downtime, maintenance costs and loss of revenue. In fact, we are now using microprocessor technology to develop prognostic capability, or the ability to predict failures before they occur through live-time monitoring and computer analysis of system operation.

Automating service functions provided to transit properties has also shown great potential for improving our customers' operational efficiency. By applying state-of-the-art computer and telecommunications technologies to areas such as ordering and cataloging of spare parts and inventory management programs, we can reduce the transit operator's cost of keeping his system operating. Computerized reliability and maintainability analyses can also help identify recurring trouble spots and develop improved maintenance procedures for dealing with them.

In the longer term, we at Westinghouse believe artificial intelligence techniques as a quality improvement tool can be applied successfully to transit applications. We are working on AI programs now to improve both the speed and accuracy of diagnostic effort for reduced transit system down time.

Development of stronger, yet lighter weight materials will also yield significant cost savings and quality improvements in the future for transit equipment by reducing weight and cost while extending design life.

As equipment designers and manufacturers, we have also addressed the application of new technology to the process side of our business. This effort has been in response not only to the demands of the marketplace, but also to the aggressive innovations in this area aimed at improving quality initiated by offshore competitors, particularly in Japan.

A key focus in this area is the development of automated production techniques using real-time computer-based management information and production management systems for every phase of the business from marketing through product warranty.

This effort has been coupled with supplier management programs to reduce the cost and cycle time while improving the quality of purchased materials and components. Factory modernization programs with a variety of process flow enhancements including transfer lines and more sophisticated warehousing have been completed to enable further reductions in our total process cycle time.

Computer-assisted engineering, design and drafting, and manufacturing capability must also be an essential, integral part of any suppliers' process quality improvement program. Investments in CAE, CADD and CAM programs have proven dramatically their ability to reduce the human errors in design and manufacturing that contribute to poor product quality.

Finally, a variety of proven quality enhancement tools are being employed to address the productivity, quality and cost targets that we have set for ourselves, and that our domestic customers have set for us. These include training and skill enhancement programs, value analysis techniques, quality circles where employes work together to solve quality problems, and planned quality improvement programs designed for monitoring with measurable results.

This review of some of the quality improvement activities underway by suppliers today reveals several important facts. First, manufacturers are responding to the needs of the domestic transit market for innovation to improve quality and operational efficiency and to reduce cost. Second, there are a wide variety of ways that innovative new technologies have been and are being applied to transit applications. Third, we have seen that while industry is doing a lot with technology for transit, it could be doing more, more quickly.

BARRIERS TO INNOVATION

The fact is that technology developments in the U.S. transit industry have been generally slow, sporadic and evolutionary. This is due in part to the conservative nature of the properties themselves and the technical consultants who advise them, and in part to the lack of a broad-based national policy of expanding transit technology and infrastructure in this country, including very limited government funding for basic research and development.

For example, the first prototype AC drive for transit service was actually introduced in Cleveland back in 1968. Cost efficient power devices weren't available then to make the concept practical for revenue service. However, it has taken almost 15 years to move this technology forward in the transit industry, and now only by applying new device technology developed elsewhere.

Westinghouse first developed linear induction motor technology in World War II as a catapult for aircraft to take off from short runways. This technology has been around ever since, but is only now reaching practical application.

The concept of artificial intelligence has had 15 years of development activity in the academic world, primarily in the fields of medicine and petroleum exploration. Only now is it being thought of for transit, but industry supported R & D is still non-existent.

There are important structural characteristics of the market that have also discouraged technology investment on the part of suppliers. Sluggish, often erratic, market volumes make investment planning uncertain at best. In the U.S. market, there is no assurance of base volume for suppliers from which to support broad strategic technology development like that which has occurred in Europe and Japan. Also, increasingly tough contract requirements, contractor liabilities, MIL specs and so forth have increased risk for suppliers and discouraged technological aggressiveness.

For all these reasons, it is fair to say that the U.S. market has lagged behind other world markets in developing and applying new technologies to transit. Germany and Japan, for example, have invested heavily in R & D to position themselves as world technology leaders in transit. Their activities cover a large variety of new technologies from belt driven systems to high speed magnetic levitation.

Foreign nations in general have been more receptive to innovative technology and have supported their industry's R & D activity in a timely fashion. I believe we can embark on a similar path.

JOINT DEVELOPMENT PROGRAMS NEEDED

The U.S. transit industry has all the talent and capability required to meet or exceed the achievements of foreign nations in transit technology innovation. Our focus today is appropriately on quality and cost improvement to assure the continued economic viability of our nation's transit systems.

Whether our long term focus in the U.S. remains on quality improvement of existing technologies or expands to embrace higher performance systems using more innovative approaches, user transit properties and their suppliers should share the risk of further development through jointly-funded R & D programs. Together we must bring more quickly into revenue service the innovations and advancements in both hardware and software products and services that address the needs for quality and performance of U.S. transit systems, today and in the future.

We have achieved a great deal in the domestic transit community, but the continued health of our transit system infrastructure depends on three-way operator-government-supplier cooperation toward innovative solutions to the key issues facing our industry. Other nations have met these challenges and made a cooperative effort work for their common good...so can we.

Operational Experience — Rail

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ASYNCHRONOUS TRACTION EXPERIMENTS ON THE PARIS METRO

P. Griffe
R.A.T.P.
France

Rolling stock MI 79 Photo RATP

The inception of static control techniques of traction motors using power semiconductors on Paris metro dates from 1970 when the first prototype current chopper motor car was commissioned for passenger use.

At that time the RATP had embarked on a vast renewal program of its rolling stock fleet. The cars were green and red in color and were familiar to all who had ever been in Paris. They had been built at the turn of the century, some fifty years previous.

The success of this first current chopper motor car encouraged the management of the RATP to abandon the old technique of direct current control of motors by contactors and camshaft, and adopt the new technique in continuing the renewal of the car fleet, despite the increased cost. The RATP has never regretted this decision, since the solution involving DC choppers has borne out the hopes of increased comfort, reliability and improved performance in regard to energy saving and maintenance cost.

Meanwhile the technique was evolving rapidly and the RATP, together with its contractors Alsthom-Atlantique, TCO and Jeumont-Schneider, decided to pave the way for the future by fostering the development, first of current chopper technology, and second, parallel with this, an experimental program covering asynchronous motor traction with inverters.

These experiments will permit the testing of different solutions such as the voltage inverter, the current inverter or again the new technologies, that is, microprocessor controlled electronics or power semi-conductor cooling by transformation of a "Freon" type liquid to a gas phase, followed by condensation.

Following a short run-through of the Paris metro system and its rolling stock fleet this paper will consider the test program on asynchronous traction.

Paris metro system

The railway network operated by the RATP covers

- The narrow gauge Metro with cars 2.40 m wide, currently serving intra-muros Paris plus the near suburbs. The traffic of a workday is 4,35 million of passengers.

- The regional express metro system (RER) with the UIC gauge, serving the outer suburbs and crossing through Paris. The traffic of a workday is 0,98 million of passengers.

Table 1 gives the main data on the two systems which carry nearly 5,4 million passengers a day.

	Metro	RER
No. of lines	15	2
Length of lines :	192 km	103 km
. Paris	158 km	20 km
. Suburbs	34 km	83 km
Designated stations	286	62
Power supply	750 V DC	1 500 V DC
Width of cars	2.40 m	3.0 m
Number of passengers per work day	4,35 million	0,98 million

Table 1 - HIGHLIGHTS OF PARIS METRO AND RER

Rolling stock

The metro has 4 lines running on pneumatic tyres (see Table 2), totalling 927 cars. The remaining 11 lines of the system runs on steel/steel wheels covering two main types of cars : the MF 67 (1483 cars) and the MF 77 (935 cars). Almost all of this fleet has been built between 1963 and 1983.

Line A of the RER (see table 3) is equipped with MS 61 stock (381 cars), built between 1967 and 1980. The fleet is scheduled to be completed by 1985 with MI 84 dual current rolling stock (1500 V DC and 25,000 V, 50 Hz) now under development.

Line B of RER is equipped with the older type Z cars (147 motor cars) which are gradually being replaced with MI 79 stock (80x4 cars sets currently in operation). The stock is dual current and is able to negotiate the northern part of Line B operated by the SNCF at 25,000 V 50 Hz, and the southern part operated by the RATP at 1500 V DC. This rolling stock, which was jointly developed by the RATP and the SNCF, makes it possible to interconnect the two systems and fosters the transit of suburbia to Paris and vice versa.

Type of car : MF steel/steel wheels MP pneumatic tires 55 - date of test	MP 55 MP 59 MP 73	MF 51 articulated	MF 67	MF 77	TOTAL
Put into service	1956-1975	1951-1953	1967-1978	1978-1982	-
Equipped lines	1, 4, 6, 11	10	2, 3, 3bis 5, 9, 7bis	7, 8, 13	-
Number of motor cars	612	100	904	561	2 177
Number of trailers	315	-	579	374	1 268
Total of cars	927	100	1 483	935	3 445
Nominal passengers capacity of 5 cars train - 3 M + 2 T	806	747	806	800	-
Maximum speed	80 km/h	"	"	100 km/h	-
Traction equipement	DC motor Camshaft	"	"	DC motor Chopper	-

Table 2 - ROLLING STOCK OF THE METRO

Type of car	Z	MS 61	MI 79
Put into service	1936-1962	1967-1980	1980-1984
Equipped lines	Line B	Line A	Line B
Number of motor cars	147	254	164
Number of trailers	-	127	164
Total of cars	147	381	328
Train or unit composition	7 M	2 M + 1 T	2 M + 2 T
Capacity of a train or unit	1 785	858	1 107
Maximum speed	100 km/h	100 km/h	140 km/h
Traction equipment	DC motor Camshaft	DC motor Camshaft	DC motor Chopper

Table 3 - ROLLING STOCK OF RER

Current choppers on the Paris metro

Before coming to the experiments on asynchronous traction on the Paris metro it may be appropriate to review the RATP experiments on chopper controlled direct current motors, as well as the highly significant results obtained with the latter system which has now shown its merits and has not ceased to evolve.

By the end of the 60's, the RATP given the progress made in the area of power semiconductors, had started to look into the possibilities of static control systems for motors. Three prototype motor cars were commissioned for passenger service in the course of 1970-1972, to investigate the various technological solutions. Given the highly encouraging results, the RATP decided in 1973 to build a prototype train, then to generalize this type of equipment (DC motor + choppers) on rolling stock delivered starting from 1977, not only on the metro (MF 77 cars) but on the RER (MI 79 cars).

Today 30% of the metro fleet has been fitted with choppers ; by the end of 1984 the entire fleet on Line B of the RER will be similarly fitted.

Table 4 gives the main particulars on both type of car.

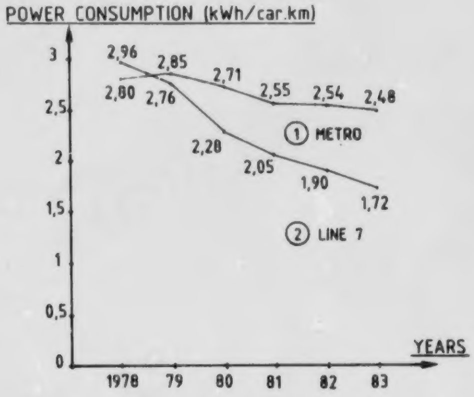


Figure 1 - POWER CONSUMPTION (kWh/car km)
(1) average rate on the whole Metro
(2) average rate on the line 7 which has been progressively equipped with new cars MF 77 (regenerative braking).

It is scarcely necessary to run through the known advantages of current choppers which have been described in many publications, amongst others : better use of wheel grip, improved passenger comfort, reduced fatigue of mechanical components, etc.

Mention will be made here only of the spectacular results obtained in the matter of energy saving.

Figure 1, shows how energy consumption on the metro in general, and on line 7 in particular, has envolved between 1978 and 1983 with the gradual introduction of the chopper-equipped MF 77 stock with regenerative braking. On line 7, which is now entirely fitted with MF 77 stock, energy saving is better than 40%, although the new cars are a little longer and heavier than the old ones and although the power consumption for the auxiliairies are more important because of the forced ventilation of the cars. The results obtained in the field after a few years operation, have corroborated the results of computer simulations which had been conducted earlier, and had led to conluding on the good receptivity of the supply lines in electrical energy.

The RATP has not had to regret its decision to abandon rheostatic braking, and to opt only for regenerative braking. True, this result was also made possible by the design of the electrical supply system, as well as the relatively short inter-station distances on the Paris metro, which on line 7 is around 600 m.

Development of current chopper

In view of the positive results obtained with this type of equipment, and given the technical trends in general and of power components in particular in the course of the past two years, the RATP has launched out on a period of reflection jointly with the manufacturers of its MF 77 and MI 79 stock, Jeumont-Schneider and TCO, regarding the development of second generation choppers of which the prototypes are already under test.

They are fitted to 17 MF 77 trains to be delivered starting end 1984, and to some sixty MI 84 sets scheduled for line A. Table 4 shows their main characteristics.

The latest generation choppers make the fullest use of the performances of recent power semiconductors, namely voltage, current and commutation speed. The introduction of microprocessor technology will allow to decrease the control electronics volume and to improve the reliability. Lastly, forced ventilation to cool the power semiconductor chips has been replaced by immersion cooling in a Freon type liquid coolant. This solution which has been tested on a chopper unit prototype since 1979, has been chosen for the MI 84 rolling stock. In addition to the gain in weight and the increasing compacture of the equipment, the Freon cooling allows the elimination of the blowers which are always a noise source, . The cleaning of the equipments will be easier because the electronic components will be sheltered from environmental pollution by dust.

	METRO		RER	
	MF 77 1st generation	MF 77 2nd generation	MI 79	MI 84
Put into service	1978	1985	1980	1984
Train composition M : motocar - T : trailer car	3M 2T	"	2M 2T	"
Number of passengers (4 P per m2)	575	"	843	"
Maximum speed	100 km/h	"	140 km/h	"
Traction voltage	750 V	"	1 500 V DC 25 000 V 50 Hz	"
Number of traction motors X motor rating per car	2 x 265 kW	"	4 x 370 kW	"
Control capacity per chopper	300 kW	600 kW	900 kW	"
Pulse frequency	300 Hz	600 Hz	300 Hz	"
Traction braking	Static	"	Elect.mechanical	"
Braking excitation system	Self excitation	"	Separated excitation	Self excitation
Electric brake system	Regenerative	"	Rheostatic and regenerative	Regenerative
Electronic control device	Standard	Microprocessor	Standard	Microprocessor
Cooling system	Air forced ventilation	"	Air forced ventilation	Freon

Table 4 - THYRISTOR CHOPPER CONTROLED TRAINS OF PARIS METRO

Experimental asynchronous traction

If as was stated earlier, from the start of the 70's the RATP opted for the DC/Chopper motor solution to complete its renewal of the rolling stock fleet, it was because at the time the solution was manifestly the most economical. However, the progress that has since been made in the area of electronics, in the widest sense of the term, has opened up other approaches, and in particular the use of asynchronous motors.

Figure 2 - Photo RATP
ASYNCHRONOUS MOTOR CAR M 10 024

Which was why, to be in a position to effect the optimum choice for the forthcoming series of rolling stock to be renewed in the 90's the RATP undertook as early as 1977 a number of feasibility studies, jointly with the contractors of railway equipment Alsthom-Atlantique TCO and Jeumont-Schneider, in order to optimize the asynchronous traction chains. The studies showed that many solutions were feasible and that it was difficult to arrive at the optimum solution, even if the solutions were limited solely to the Paris Metro.

Take the sole factor of maximum rotational speed of the motor, which is not, as in the case of the DC motor related to the peripheral speed of the commutator, there is a number of interesting solutions at conventional speeds such as 3000-4000 rpm, and even at speeds of around 6000 rpm which appear to be a maximum at the present time

Conceivably the economic and technological optimum may well be not the use the high rotanal speed achievable with asynchronous motors, as these impact adversely on the reducing gear cost, sturdiness of the motors, and noise.

The studies emerged on the construction of a prototype motor car by each of the three companies named. Table 5 gives the major features of the three motor cars which will enable us to test out various technical solutions.

Motor car M 10.024 made by Alsthom-Atlantique

Motor car M 10.024 of the rolling stock series MF 67, was retired from the reserve fleet at the start of 1980 to undergo conversion. The conventional equipment was removed and in its stead ar asynchronous motor of 250 kW was mounted on each motor bogie, and two pulse wide modulation inverters with direct feed-in were installed under the bodyshell (figure 2). The target was to test at the minimum cost the PWM inverter without searching to optimize the asynchronous traction chain. Thus the motor maximum speed has been chosen at the same rate of the DC motor 2670 rpm so that the reducing gear was not changed.

Motor car number	M 10 024	M 30 029	M 30 125
Manufacturer of the traction equipment	Alsthom-Atlantique	T.C.O.	Jeumont-Schneider
Date of test	End of 1981	November 1983	December 1983
Put into service	June 1982	1984	1984
I - CARS			
Type of car	MF 67	MF 77	MF 77
Weight	27 200 kg	27 000 kg	27 000 kg
Weight with passengers	38 190 kg	37 980 kg	37 980 kg
Sizes of the cars : widht	2,40 m	2,46 m	2,46 m
length	14,39 m	15,47 m	15,47 m
height	3,42 m	3,42 m	3,42 m
Maximum speed	80 km/h	100 km/h	100 km/h
Electric braking	Regenerative	Regenerative	Regenerative
Bogie type	Monomotor	Monomotor	Bimotor
II - MOTORS			
Rated power	250 kW	280 kW	125 kW
Maximum speed	2 670 rpm	3 310 rpm	5 400 rpm
Number of poles	6	4	4
Maximum voltage between phases	317 V	350 V	329 V
Maximum phase current	350 A	500 A	250 A
Weight	1 200 kg	900 kg	500 kg
III - CONVERTER			
Type	PW M inverter with direct feed in	Chopper current inverter	Chopper current inverter
Power supply	750 V DC	750 V DC	750 V DC
Voltage variations	450 V - 900 V	450 V - 900 V	450 V - 900 V
Number of motor per converter	1	1	2
Input chopper	NO	YES	YES
Pulse frequency		600 Hz	600 Hz
Maximum mean current		650 A	525 A
Inverter			
Maximum frequency	135 Hz	115 hz	180 Hz
Maximum output voltage	550 V	718 V	570 V
Maximum output current	360 A	510 A	500 A
Sub chopping	PWM	PWM	NO
Cooling system	Freon	Freon	Air
Electronic control device	Conventional	Microprocessor	Conventional

Table 5 - MAIN FEATURES OF ASYNCHRONOUS TRACTION EXPERIMENTATIONS ON THE PARIS METRO

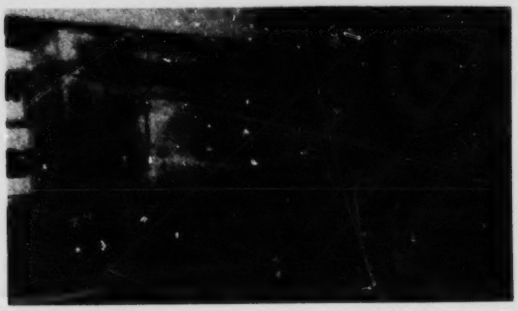


Figure 3 Photo RATP

ASYNCHRONOUS MOTOR CAR M 10.024
FREON COOLING SYSTEM

Next the fine tuning took place on the RATP's trial track at Sucy-en-Brie. Aside from the inevitable debugging, the trials covered a great many tests on the electromagnetic compatibility of the motor car with the signal system.

The fact is that in common with all gear operating by voltage or current pulses, the motor car generates fluctuations in the traction current at varying frequencies, which are liable to disrupt the track circuitry of the signalling system on account of conduction and radiation ; and hence in general, all of the safety equipment.

On the Paris metro many generations of track circuitry coexist. The eldest operate at a supply of 50 Hz ; they are extremely sensitive to direct voltage inverters, which cause the frequency of the supply voltage of the asynchronous motor to fluctuate from 0 to 120 Hz. These track circuits have for some years been replaced by more advanced equipment, of which the following may be mentioned :

- Jeumont-Schneider high voltage impulsing(ITE) track circuits, with and without joints ;
- Alsthom-Atlantique jointless track circuits operating at frequencies of 8.2 - 12.3 kHz ;
- CSEE jointless circuits operating at frequencies of between 1700 Hz and 2600 Hz ;

A measuring compaign was undertaken to determine the level of the harmonic lines in currents generated by the traction equipment, with the following results :

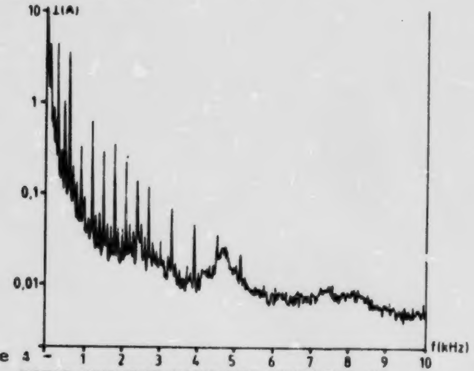


Figure 4 MOTOR CURRENT HARMONIC ANALYSIS OF THE ASYNCHRONOUS MOTOR CAR M 10 024
I = 80 A - Range 0-10 kHz

- In the frequency spectrum of the return current are found all of the harmonic lines of the stator frequency (of which one example is shown in the figure 4 ;
- Beyond 1000 Hz, the lines no longer generate background noise and only remain in the spectrum as lines related to ripple in the voltage lines.

To conclude, research has shown that there was no likelihood of disturbance on modern track circuitry ; but as against this, that current levels at 50 Hz were distinctly higher, while remaining within acceptable limits. Hence the motor car was authorized to run on the system, provided however that it was the only one of its kind on the line on which it was operationnal.

The motor car has now become part of a passenger trainset on line 3bis from Gambetta to Porte des Lilas. In october 1983 the motor car had run 20.000 km without noticeable failure, showing the feasibility of this solution.

TCO motor car M 30.029

Asynchronous motor car M 30.029 was derived from the conversion of a motor car of MF 77. The performance of the earlier car was kept i.e. top speed 100 km/h, acceleration 0.9 m/s2 in traction, and 1.15 m/s2 in braking.

The DC motors of the two single-motor bogies were replaced by asynchronous motors of 280 kW, 4-pole,rotating at a little higher maximum speed of 3310 rpm instead of 2 670 rpm, the reducing gear has been changed.

In this project the chopper/current inverter solution was opted for, in which each motor is controlled by an inverter. The control electronics is by microprocessor, thereby facilitating the introduction of sub-chopping of the starting current wave in order to reduce the pulsatory torques.

As in the M 10.024 motor car,the power semiconductors are cooled by immersion in Freon type coolant. Motor car M 30.029 is undergoing its initial tests at the maker's.

Its commissioning as part of a passenger train is scheduled for the beginning of 1984.

Jeumont-Schneider motor car M 30.125

As with the previous one, this project uses the bodyshell of an MF 77 motor car. But Jeumont-Schneider has come out with another type of bogie. This one is articulated, and in contrast to that of the standard series MF 77, it is twin-motor.

The bogie is fitted with two 125 kW asynchronous motors. Top speed was chosen to be a relatively high 5400 rpm, which is therefore in the top bracket of maximum speeds of the asynchronous motors used on metros and light rail transit. The motor is self-ventilated. A two-step reducing gear operates between motor and axle.

Underfloor are installed two chopper-current inverters each controlling both motors on the same bogie. The control electronics are conventional, as is also the cooling of the semiconductor chips.

The conversion of the motor car is nearing completion. The initial runs on the trial track are scheduled for december 1983.

Merits of the asynchronous system on RATP lines

A significant part of the rolling stock fleet of the Paris metro has, as we saw earlier, been fitted with choppers. In this way the RATP has been in a position to gauge the appreciable advantages imparted by static control of the two traction motors with the use of the power semiconductors, e.g. :

- Continuous control of the tractive force, hence better use of wheel grip and improved passenger comfort ;
- Reduced maintenance cost, and in particular on brake components ;
- Energy saving, as has already been discussed.

Yet the asynchronous traction is not likely to induce any very significant progress in this respect. The most one may expect in regard to performance is better rate of energy recovery at high speeds. But this is seldom achieved on a system with short interstation distances. Another feature is that design-wise, there is better integration of the motors in the bogies due to their reduced bulk at equal power.

Ultimately the features that will distinguish between DC motors and asynchronous motors is capital investment and maintenance costs.

As regards outlay, there is on the one hand a complex motor with simple electronics, and on the other hand a simpler motor with more complex electronics.

As regards maintenance cost, it is generally agreed that the asynchronous solution is the more economical on account of the simplicity of its motors. Yet this judgement is subject to comments. For indeed the design of traction motors has undergone a vast improvement over the past twenty years, especially in regard to insulation. Today makers are able to build DC motor which in the area of metros, give no trouble in operation.

On the Paris metro, DC motor generally run an average of 600.000 km between overhauls. In between these, the only servicing calls for replacing the brushes every 200.000 km.

It would not seem, as things stand today, that the savings brought about on such servicing might in themselves justify the fitting of asynchronous motors.

Conclusion

The experiments with asynchronous traction described above are just part of a more wide-ranging investigation by the RATP on the organization of public transportation in the Greater Paris area at the end of this century.

The metro of the year 2000 will not differ fundamantally from that of today, at least in regard to its major feature -- it is difficult to rebuild its stations and tunnels.

As against this, it is certain that the technical configuration of the trains will encompass the latest innovations, especially in regard to electronics and electrotechnic. One part of the major innovation is certain to be the transmission of the drive force. But it is difficult to forecast today what is likely to be the most effective solution, if one takes into account both the capital outlay and the maintenance costs. The evolution of power semiconductors may have a favorable impact on the development of many solutions. It is reasonable to suppose that given the immense possibilities opened up by modern technology, each metro system will identify the optimum electronic compromise for motor control to satisfy its own requirements, whether the motor be DC, asynchronous -- or even synchronous.

References

Rajeunissement d'une vieille idée.

La RATP et Alsthom-Atlantique expérimentent le moteur asynchrone sur une rame de Métro.

Jacques Soffer et André Pascal RGCF Septembre 1982.

ELECTROMAGNETIC COMPATIBILITY OF AN OPERATING AC PROPULSION SYSTEM — PRACTICAL EXPERIENCE OF THE HELSINKI METRO

Jouko Karvinen
Kymi-Strömberg OY
Finland

Summary

The implementation of advanced AC drive technology in urban rail transit systems offers many advantages, like good reliability and reduced maintenance costs. However, this step of the propulsion development has also arised a concern of potential electromagnetic interference problems. This paper describes the electromagnetic compatibility characteristics of an operating AC propulsion system in revenue service, the Helsinki Metro. The main subject of the discussion is the compatibility with track circuits used for train detection.

In addition to the fact that the AC propulsion system has shown good compatibility with the particular train detection system used in Helsinki, it has also given a good chance to experimentally test overall EMI characteristics of the AC propulsion.

1. Helsinki Metro AC propulsions

Each of the Helsinki Metro cars is equipped with two PWM- (pulse-width-modulation) controlled thyristor-inverters. Because the smallest functional unit is a car pair, the AC propulsion consists of four parallel-connected inverters (truck drives $DR_1 \ldots DR_4$), of which each feeds two 128 kW, totally enclosed fan-cooled squirrel cage motors. One of the cars of a car pair has also a static auxiliary inverter (AI) that feeds the auxiliaries of both cars. A block diagram of the main circuits of a car pair is shown in Fig. 1.

The third rail power is fed to the cars via two current collector pairs (one collector on each side of the car) located at each end of the car pair. For securing the third rail power for all four truck drives in line gaps there is also an intermediate cable between the DC inputs of the two cars (intercar jumper). Each inverter bridge is connected to the third rail via an inductor-capacitor circuit. The nominal third rail voltage is equal to 750 V_{DC}. Both running rails are used for propulsion current return.

The Helsinki Metro cars are non-regenerative. In braking mode the traction motors operate as generators. The braking power is fed via the DC link

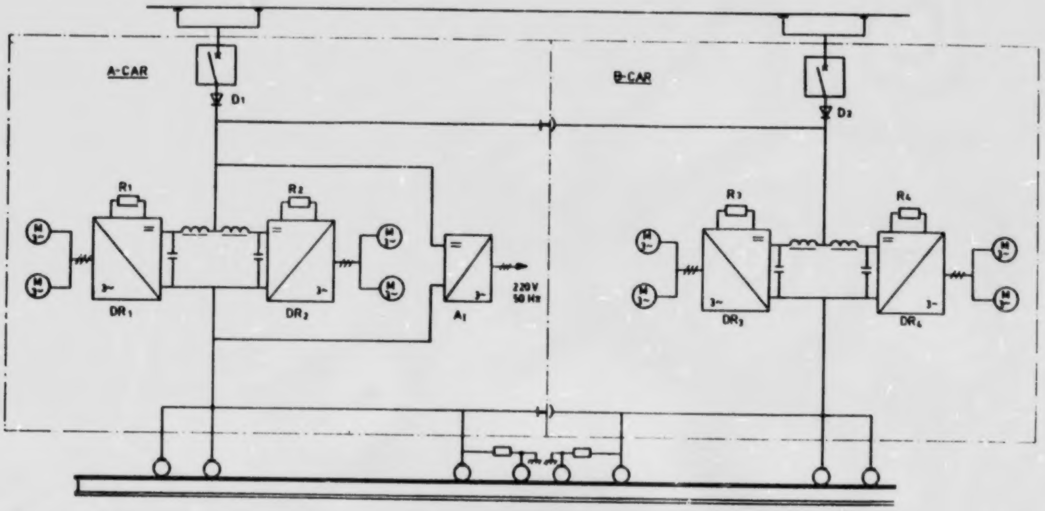
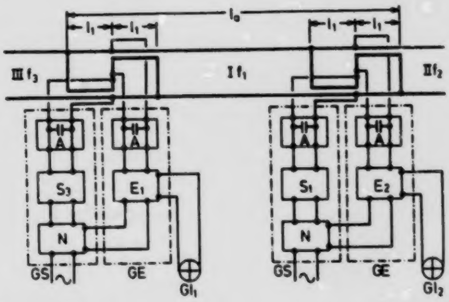


Fig. 1. Block diagram of main circuits of a car pair

and via a braking chopper to a braking resistor ($R_1 \ldots R_4$). Most time of the year this power can be used for car heating. The linediodes (D_1, D_2) are back-biased in braking mode.

2. Audio frequency track circuits of the Helsinki Metro

The Helsinki Metro uses an audio-frequency type track circuitry for track clearance/occupancy detection. (SIEMENS Gl S 9/15). The system requires no physical rail joint insulation equipment for normal track section isolation. The isolation is realized by an electric demarcation, thus permitting the continuous welding of the running rails. A principal diagram of a track section is shown in Fig. 2.



A	Tuning unit
S_1	Transmitter for track section I
S_3	Transmitter for track section III
E_1	Receiver for track section I
E_2	Receiver for track section II
I, II, III	Track sections
l_a	Length of section
l_1	Half-length of S-bond
N	Mains pack
Gl_1	Track relay for section I
Gl_2	Track relay for section II
GS	Transmitter housing
GE	Receiver housing

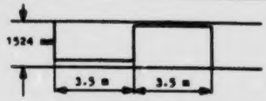
Fig. 2. Basic AF Track Circuit of the Helsinki Metro[1]

Transmitter S, located at the beginning of the track sections feeds an audio frequency voltage into the track. Receiver E, which is tuned to the respective transmitting frequency is located at the section end. Receiver supplies a constant power output for the feed of track relay Gl. With occupied track the input level of the receiver falls short of set rating and its output power drops abruptly to null.[1]

Key technical characteristics of a typical track circuit are given in Table 1.

TABLE 1

Technical Characteristics of a Typical Track Circuit of the Helsinki Metro (standard layout) [1,2]

Min. Ballast Resistance (S-bond, 240 mm^2	1.5 ohm · km
Electrical joint	
Operating Frequencies	TRACK I: f_7 9.5 kHz, f_8 11.5 kHz, f_9 13.5 kHz PARALLEL TRACK II: f_{10} 10.5 kHz, f_{11} 12.5 kHz, f_{12} 14.5 kHz
Track Voltage	$U_{transmitter}$ = 3...10 V $U_{receiver}$ = approx. 0.3 V
Track Section Length	l_a = 300...350 m

3. AC drive as a source of electromagnetic interference

3.1. General

Strömberg's know-how about the EMI-characteristics of AC drives is mainly based on the following methods:

1. computer simulations (analytical predictions)

2. laboratory measurements

3. track tests with complete vehicles

The combination of these three methods has given essential information about the characteristics of not only one drive but also of the interaction and net effects of several drives on the EMI. It has also given good guidelines for the design-options necessary for various types of signalling circuits.

3.2. Conducted EMI of the Helsinki Metro AC Propulsion

A voltage-fed PWM-inverter can be characterized as a source for harmonic currents connected across the terminals of the DC link capacitor.[3]

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By means of computer simulation it can be shown that typical harmonic frequencies appearing in the DC link of a PWM-inverter are equal to:

$$f_n = k \cdot 6 \cdot f_o \qquad \begin{array}{l} k = 1, 2, 3 \ldots \\ f_o = \text{inverter output frequency} \end{array}$$

The source of the sixth harmonic is the content of the 5. and 7. harmonics in the PWM-controlled output voltage of the three-phase inverter. Correspondingly, the 12. harmonic is attributable to the 11. and 13. harmonics of the AC voltage. For a symmetrical three-phase system the DC link current harmonics having a frequncy equal to k 6 f_o are caused by the AC voltage harmonic pairs, which have a frequency equal to $(6 \ (k \mp 1)) \ f_o$.

The characteristics of the generation of the DC link harmonic currents gives a basic guideline for the design of the PWM-voltage control of an inverter drive that is to be operated with power frequency track circuits. The low-order harmonics (5. and 7., 11. and 12. etc.) must be cancelled as carefully as possible in the operation area where the inverter output frequency is low.

This complies well with well-known requirement of the reduction of low-order harmonics in order to minimize the losses and torque pulsations of the AC traction motors when operating at low frequencies.

Because the minimization of low-order harmonics of the inverter output voltage by means of various PWM-methods has been described extensively in the literature, the subject is not investigated here.

The small unsymmetries appearing in all real systems affect also the harmonic content of the DC link current, causing harmonics at the frequencies equal to f_o, 2 f_o etc. The amplitudes of these harmonics in a well-balanced system are, however, relatively low.

The DC link current harmonics caused by the inverter are damped by the network consisting of the LC-circuit of the individual drive, LC-circuits of parallel drives and line impedance. A simplified circuit diagram of the network is shown in Fig. 3.

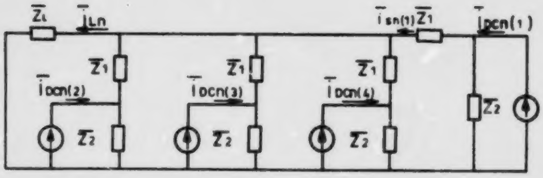

Fig. 3. Principal circuit diagram of the network attenuating harmonic currents caused by the inverter

By analyzing the transfer function between a DC link current harmonic component of an individual drive $i_{DCn\ (1)}$ and the corresponding line current harmonic component $i_{Ln\ (1)}$ caused by $i_{DCn\ (1)}$, it can be shown that:

$$\frac{\overline{i}_{Ln\ (1)}}{\overline{i}_{DCn\ (1)}} = \frac{\overline{Z}_2}{\overline{Z}_1 + \overline{Z}_2 + k \cdot \overline{Z}_L}$$

k = number of parallel-connected drives

The effective line impedance damping the conducted interference of an individual drive is multiplied by the number of parallel-connected drives.

In order to predict the total harmonic amplitudes of the line current (i_{Ln}) generated by multiple sources ($i_{DCn(i)}$), the harmonic line current components (i_{Ln} (i)) generated by individual drives can either be algebraically added or statistically summed.[4,5]

The effect of multiple drives is especially essential concerning low frequency harmonics close to the resonance frequency of the LC-circuit.

In the audio frequency range used for train detection in Helsinki (9.5...14.5 kHz), the conducted harmonics of the inverters are practically totally filtered by the LC-network. The AF currents produced in the DC link circulate through the DC link capacitor. Only a negligible amount of these currents goes to the line.[5]

In order to give to the reader some idea of the track tests made at the Helsinki Metro, an example of an experimental time domain analysis is shown in Fig. 4. The main idea was to verify the effect of multiple drives on the damping of inverter caused harmonics that have a frequency close to the resonant frequency of the individual LC-circuit.

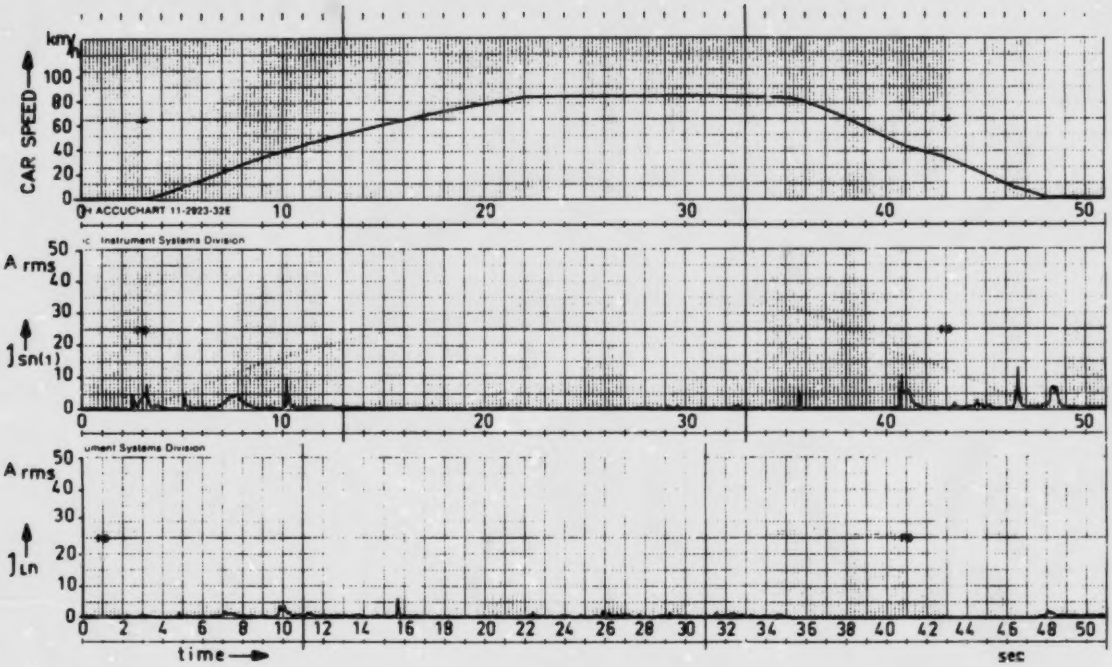

Fig. 4. Time domain-analysis of the amplitudes of 75 Hz harmonic components of the DC input current of an individual inverter drive ($I_{Sn\ (1)}$) and of the total line current of a two-car train (I_{Ln}) (Tests at the Helsinki Metro, 1982)

Both the total line current of a two-car train (I_L) and the DC input current of an individual truck drive (I_S) were measured and tape-recorded. The tape-recorded currents were band-pass-filtered (± 33 dB/oct, f_{BP} = 75 Hz) and rms-rectified ($I_{Sn\ (1)}$ and I_{Ln}).

The current of an individual drive contains relatively high amplitudes of 75 Hz harmonic current. However, the net current of the four drives has a lot lower amount of the same harmonic current. This is due to the fact that the resonance frequency of the total network is in the order of 30...35 Hz, meanwhile the resonance frequency of the individual LC is about 53 Hz. The ampere values of the currents should not be considered as absolute because the Metro propulsion and especially its LC-circuit is not designed for a power frequency signalling system.

In many propulsion applications it is advantageous to use a DC input chopper between the line and the inverter bridge. In tractive mode this line chopper operates as a step-up chopper and in regenerative braking mode as a step-down chopper. The main power circuit of the chopper is identical to a phase of the inverter. The main features of using the input chopper are:

1. control of the system performance independent of line voltage fluctuations

2. fast and accurate control of both traction and regeneration currents

The line chopper causes also a certain amount of harmonic distortion to the line current. The frequencies of the line current harmonics caused by the line chopper can be expressed by the equation

$$f_n = k \cdot f_{ch}$$

k = 1, 2, 3...
f_{ch} = line chopper operating frequency

Analytical prediction of the amplitudes of the line chopper caused harmonics is based on a simple switch model. Comparison between experimental measurements and the prediction agree well.

There are basically two ways of optimizing the conducted EMC-characteristics of the line chopper. These are:

a) connection of an additional filter circuit to the input terminals

b) selection of a fixed chopping frequency that causes no interference at the signalling frequencies

3.3. Induced EMI

The other possible source of electromagnetic interference is the inductive coupling of current carrying components on-board a train (or current carrying third rail) and the track circuit.

As stated before the third rail current harmonics caused by the AC propulsions in the signalling frequency band of Helsinki METRO are effectively damped by the LC-circuits of the drives. This is why only the inductive coupling between the on-board equipment and track circuits is discussed here.

The noise induced by magnetic flux under a car is significant only when the car is directly over an impedance bond connection of the track circuit. This means that the noise of a train is caused basically by one car at a time.[4]

The most significant sources of flux linkages in the under-car components are the following:

1. commutation reactors
2. line chopper input reactors (when the AC drive has an input chopper)
3. dynamic braking resistor
4. cabling

The commutation reactors are air-core reactors. The minimization of the net inductive coupling to the track circuit can basically be done by locating and orientating the reactor magnetic axle optimally in respect to the rail loop and by using proper shielding. Due to several ferromagnetic structures under the car that cause a distorted asymmetric field distribution, the use of location and orientation of commutation reactors can not eliminate flux linkages, but can reduce them.[4]

The shielding of the reactors by aluminium enclosures is a simple and effective way of reducing the coupling to the track circuit.

The dynamic braking resistor carries a pulse-formed current. The flux linkages of it are normally minimized by designing the current flow pattern so that an individual coil, carrying current in one direction, is placed between two coils with a current in opposite direction.

In an AC propulsion, that has an input chopper connected between the third rail and the inverter, the di/dt -limiting reactor carries relatively high ripple currents. As mentioned before, this ripple current can be filtered out to prevent conducted interference. The minimization of flux linkages can be done by using a multiple air gap iron core reactor that is located longitudinally and symmetrically in respect to the running rails. The shielding by an aluminium housing mentioned earlier, can naturally be used also for the filter reactor.

The induced EMI characteristics of a subway car are practically impossible to predict theoretically. The resulting coupling to the track circuit has to be measured, either in a simulated laboratory arrangement or using actual vehicles. The important thing is, that all components incl. cabling are located properly in respect to each other and the running rails.[4]

Two series of inductive EMI tests have been accomplished in the Helsinki Metro. In 1980 Strömberg made a series of measurements using a method that is a combination of the methods IE01A and IE04A.

The induced rail-to-rail voltage was measured in different operation conditions of the inverter and braking chopper. In the first set of measurements the mechanical brakes were on and therefore the train did not move. The drives were operating at a minimum frequency and maximum tractive effort. Then the motor cables were disconnected and the drive units were operating in a no-load condition at various frequencies.

The maximum rms-values of rail-to-rail voltage measured during the tests are listed in Table 2.

TABLE 2

Maximum rail-to-rail voltages caused by flux linkages of under-car equipment (Tests at Helsinki Metro, 1980, Frequency Range 0...20 kHz)

STATUS OF EQUIPMENT OPERATION	MAX. RMS-VOLTAGE
Current Collector Disconnected	0.2 mV
Auxiliary Inverter Operating	1.0 mV
Inverter Operating at Different Frequencies	1.0 mV
Braking Chopper Operating	5.0 mV

The results shown in Table 2 demonstrate induced EMI levels which are extremely low.

In September 1983 the Technical Systems Center (UMTA) accomplished also a series of measurements of both conductive and induced EMI at the Helsinki Metro. The data reduction of these measurements is at the moment of writing of this paper still in progress.

4. Conclusions

The PWM-controlled inverter drives of the Helsinki Metro have shown good compatibility with the AF train detection system used in Helsinki. Although the electromagnetic compatibility is a subject that has to be analyzed for a specific AC propulsion system operating in a specific type of train detection system, the track tests accomplished at the Helsinki Metro have given a good chance to characterize the EMI-phenomena of the AC drives. The experience based on theoretical simulations, laboratory measurements and track tests gives essential support for the further design of AC drives, that are to be operated in various kind of signalling systems using either power or audio frequencies.

References

1) SIEMENS: Audio Frequency Track Circuits with Electric Separation Joint for All-Welded Tracks (Description E S BS 2 - 2530-805-101, March 1969)

2) SIEMENS: Jointless Audio Frequency Track Circuits G1 S 9/15

3) J. Kosa: The Harmonic Spectrum of DC link currents in inverters (PCI, March 1982, Proceedings pp. 38 - 52)

4) Vilas D. Nene: Electromagnetic Interference Characteristics of Advanced Propulsion Systems for Urban Rail Vehicles (Report No. UMTA-VA-06-0075-81-1, February 1981)

5) Robert Rudich: Preliminary Draft of the STARS EMI Study dd. 9 Dec. 1983

VVVF INVERTER CONTROL SYSTEM FOR ELECTRIC CARS

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Osaka Municipal Transportation Bureau
Japan

(Preface)

The greatest feature of the controlling of electric rolling stock by means of VVVF inverter is the fact that 3-phase induction motor is adopted as its traction motor. The advantages of this method are energy saving, maintenance free, high adhesion, lowered floor level and so sorth, while its demerits are inductive interference, torque pulsation, rather high cost, immatured technology and so on. Presently in Japan, the VVVF inverter controlling is being watched with keen interest as a further advanced control system than the chopper controlling.

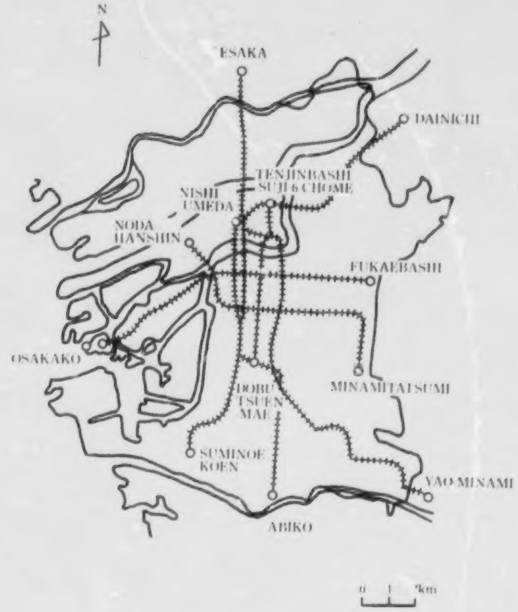
We, at the Osaka Municipal Transportation Bureau, prepared an experimental car for the VVVF inverter controlling in June, 1981, and performed an extensive test with the car during a period of July, 1981, through April, 1982. As the result of this test, the control technology with the VVVF inverter has been established, which includes the confirmation of powering and regenerative braking characteristics being the fundamental of this controlling, the solution of such problems as inductive interference and torque pulsation, the establishment of controlling method against disturbance caused by electric source or coupling of cars, etc., as well as that against slipping and skidding.

Based on the technology acquired through this test, 6 prototype cars applicable to revenue service are now under manufactured and will be completed in Mar. 1984.

In this paper, the outline of the Osaka Municipal Subway System, the status of control technology with VVVF inverter in Japan, the results of test with real car conducted by us, and the general description of our prototype car for VVVF inverter controlling are presented.

1. Outline of Osaka Municipal Subway System

The Osaka Municipal Subway System has a history of 51 years after its first section of 3.1 km between Umeda and Shinsai Bashi has been opened in May, 1933. Extension work of existing tracks and construction of new lines performed during this period expanded the System into the present scale commercially operating 6 lines with total kilometrage of 90.9 km and a fleet of 800 cars. The Line No.1 having the largest number of passengers in the System is served by 8-car trains and with 2 minute headway in the morning rush hours. A total of about 2,300,000 passengers are being transported daily by these 6 lines. Fig. 1 indicates the subway system map.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NISHI UMEDA
NODA HANSHIN
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OSAKAKO
MINAMITATSUMI
DOBUTSUEN MAE
SUMINOE KOEN
YAO MINAMI
ABIKO
0 1 2km

Fig. 1 Route Maps of Osaka Municipal Subway

At present, extension work for 3 lines totaling 9.8 km is under way, and in several years the system will reach about 100 km in trackage and about 1,000 cars in fleet. Existing 800 subway cars are composed of 704 cars with rheostatic control and 96 cars with chopper control. Table 1 shows the outline of the 6 lines.

Table 1 Outline of Lines under Osaka Municipal Subway System

Name of Line	Midosuji Line	Tanimachi Line	Yotsubashi Line	Chuo Line	Sennichimae Line	Sakaisuji Line
Section	Esaka - Abiko	Dainichi - Yao Minami	Nishi Umeda - Suminoe Koen	Osaka Ko - Fukae Bashi	Noda Hanshin - Minami Tatsumi	Tenjinbashisuji 6 - Dobutsuen Mae
Kilometrage (km)	19.5	28.1	11.4	12.5	12.6	7.0
No. of Stations	15	26	11	11	14	9
Train Composition (Car)	8	6	5	4	4	6
Headway	2'	3'	2'30"	5'	4'	2'45"
Fleet (Car)	266	216	106	52	70	90
Rail Gauge (mm)	1,435	1,435	1,435	1,435	1,435	1,435
Line Voltage (V)	750	750	750	750	750	1,500
Collection System	3rd Rail	3rd Rail	3rd Rail	3rd Rail	3rd Rail	Overhead Line

2. Status of Control Technology with VVVF inverter in Japan

In Japan, the control technology with the VVVF inverter originated in around 1976 when electrical traction equipment manufactures commenced factory test one after another. At this moment, however, only the principal of controlling by the VVVF inverter and the possibility of its application to electric rolling stock were confirmed. And at the same time, many fundamental problems, such as miniaturization for rolling stock use, improvement of efficiency by cut down of commutation loss, etc., countermeasures for inductive interference, and establishment of the optimum circuit construction, remained unsolved. Since then, each manufacturer promoted his development individually and attained to a prospective outlook for settling the problems, so that the test by a real car can be performed.

The Osaka Municipal Transportation Bureau has been keenly interested in the possible application of induction motor to the traction of electric rolling stock ever since its annuncement, and considered that it would have great possibility of replacing the chopper control. and so, to resolve the problems of the VVVF inverter controlling and to establish its control technology, we have decided to perform the test by an experimental car in March, 1980, prepared necessary equipment for the test, and executed a full scale real car test for the first time in Japan from July, 1981, to April, 1982. Owing to this test, the result of which is reported hereinafter, the control technology with the VVVF inverter could have been established, and nowadays we have entered a new phase of development where practical cars can be built.

There are 2 instances of application of the VVVF inverter controlling in Japan. One is 2 LRVs (light rail vehicles) of the Kumamoto City which were put in operation in August, 1982 and the other is 6 prototype cars of the Osaka Municipal Subway System now under manufacture and expected to undergo test running in April, 1984. While the principal specifications of the prototype cars is described hereunder, we trust that these cars, being the first real cars to be controlled by the VVVF inverter, will prove themselves to have great significance in future development and propagation of the VVVF inverter controlling. Especially, the VVVF interters under manufacture for the prototype cars, we believe, are one of the most advanced inverters for rail traction use in the world because of the facts that large capacity GTO thyristor is adopted as main element and that the thyristor is controlled with microcomputer by concentrating the essence of Japanese electronic technology.

3. Outline and Results of Test of VVVF Inverter with Real Car Conducted by the Osaka Municipal Transportation Bureau

As the circumstances of the captioned test performed by us are already stated above, hereinafter its outline and results are described.

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3.1 Outline of the Test Car

Train Composition:
2 Cars, i.e.
1 Car with VVVF Inverter and
1 car with Camshaft Controller

Line Voltage:
DC 750 V

Max. Speed:
70 km/h

Acceleration:
2.5 km/h/s

Deceleration:
3.5 km/h/s

Traction Motor:
3 Phase Cage Type Induction Motor
160 kW, 550V, 210A, 2 Motors/Car

Inverter:
Voltage Type, PWM (Pulse Width
Modulation) Method
GTO Element (2,500V, 600A)
610 kVA, Frequency 3-125 Hz

Filter:
L: 8 mH, C: 6,000 µF

Main Circuit:
Please refer to Fig. 2

Car Length:
17,000 mm

3.2 Major Test Items

(1) Power Characteristics

(2) Regenerative Braking Characteristics

(3) Torque Pulsation

(4) Vibration and Stress of Bogie Truck

(5) Slipping and Skidding

(6) Differential of Wheel Diameters

(7) Inductive Interference

3.3 Test Results

3.3.1 Powering Characteristics and Regenerative Braking Characteristics

Fig. 3 indicates typical oscillograms of powering and regenerative braking characteristics. By the combination of constant torque control, constant output control, and constant slip frequency control, the powering characteristics of the test car including acceleration is confirmed to be well matching with that of the

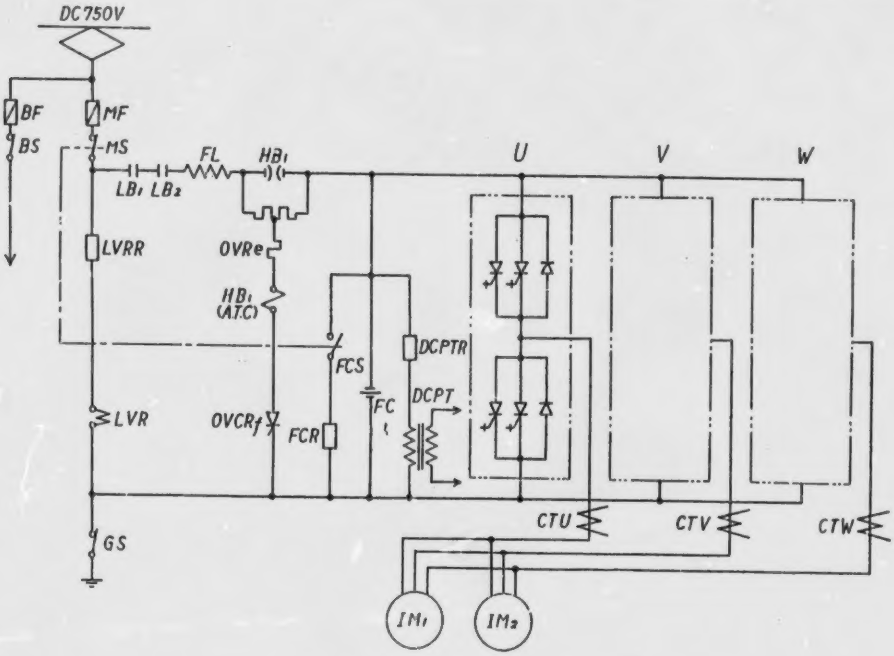


Fig. 2 PWM Inverter Circuit

car equipped with the conventional DC series-wound motors. Further, smooth acceleration was obtained without trouble in the course of notching operation, repowering, and passing over a dead section. The changeover of pulse mode was also performed smoothly.

The regenerative braking characteristics is of blended preferential regenerative brake and supplementary air brake type, and each of such functions as full braking, rebraking, shutting off regenerative load, and regenerating without load proved out to operate exactly as designed. and the regeneration ratio obtained for the running curve assuming revenue service condition was approximately 30% on an average.

Furthermore, it was found that the damping control of slip frequency is indispensable to secure stabilized operation of the system against such disturbance as the fluctuation of line voltage.

3.3.2 Torque Pulsation, Vibration and Stress of Bogie Truck

As the torque pulsation of traction motor is approximately 15% in linear acceleration range, no special countermeasures for driving gear and bogie truck are considered to be necessary. There found no problems in respect of the vibration and stress on principal portion of the truck. A typical oscillogram is shown in Fig. 4.

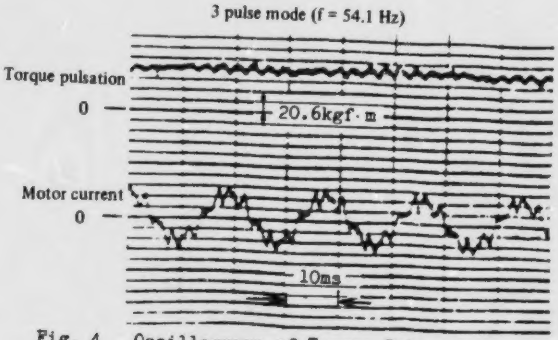


Fig. 4 Oscillograms of Torque Pulsation

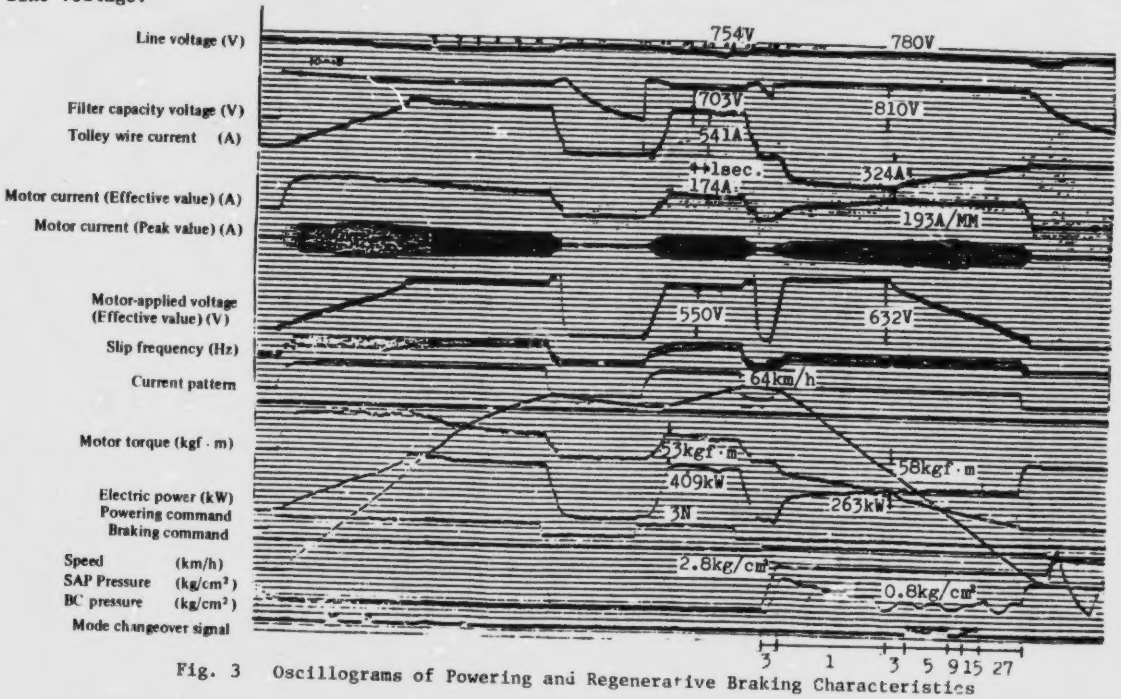


Fig. 3 Oscillograms of Powering and Regenerative Braking Characteristics

3.3.3 Slipping and Skidding

For readhesion control in the case of slipping or skidding, decreasing of the torque of traction motor by detecting slip or skid is required. And after testing several methods including the decreasing of traction motor current, the decreasing of current and slip frequency was found to be effective for the purpose. A typical oscillogram is shown in Fig. 5.

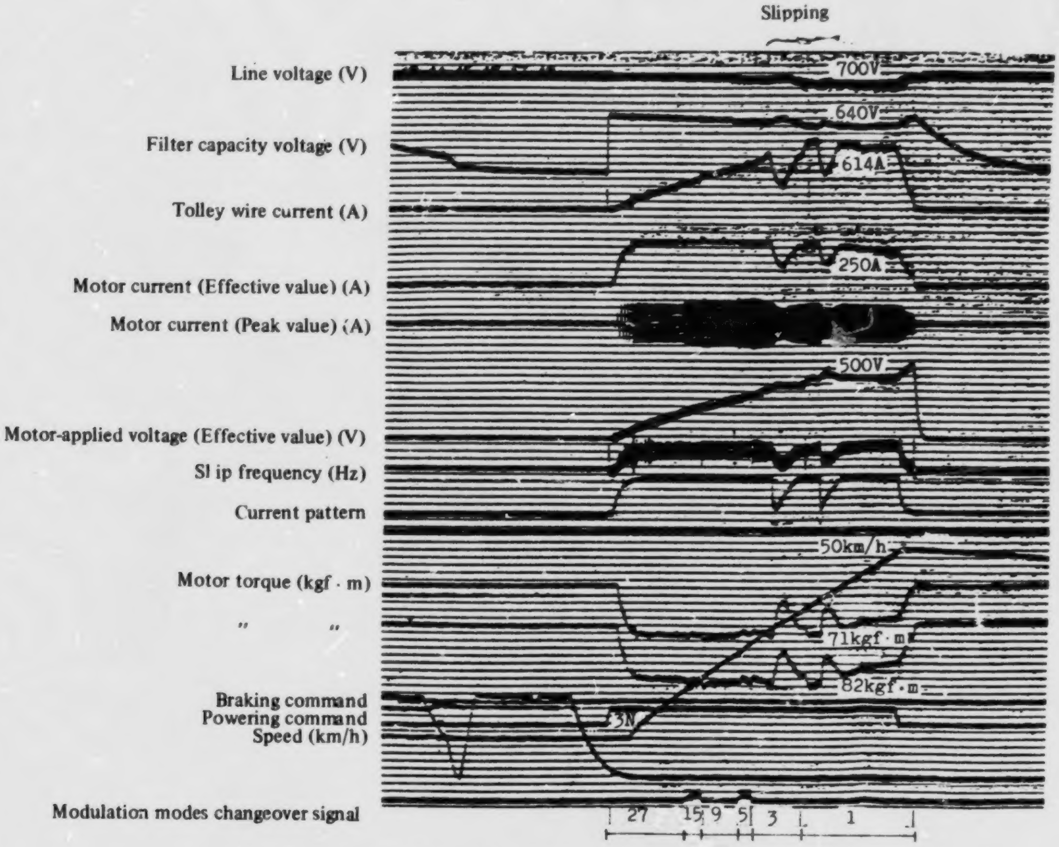


Fig. 5 Oscillogram of Slipping

3.3.4 Differential of Wheel Diameter

As the result of the test performed with a difference of 5 mm in wheel diameters (standard diameter is 792 mm), it was known that the unbalance of output torque is approximately 13% and that there is little effect on the temperature rise of traction motor. Therefore, the differential of wheel diameters in the vicinity of 5 mm is considered to be harmless.

3.3.5 Inductive Interference

The occurrence and intensity of inductive interference were checked up on the conceivable objects such as track circuit for ATC, commercial frequency track relay circuit, inductive radio circuit, telephone circuit and substation equipment. Among these objects, commercial frequency track relay circuit, inductive radio circuit, telephone circuit, and substation equipment were not affected practically. But the effect on the track circuit for ATC, particularly the effect of inductive interface noise on noninsulation track circuit, proved to be great, and a value more than the operating level of receiver was measured.

To settle these problems, relocation of reactor in inverter box and addition of shield plates as well as detection of noise source were carried out. On account of the above countermeasures, the noise was suppressed and bright prospects for solution are being anticipated.

4. Outline of Prototype Car Adopting VVVF Inverter Controlling

4.1 Principal Specifications

The principal specifications of the prototype cars and the major items of the inverter equipment are shown in Tables 2 and 3 respectively. And the powering characteristics and regenerative braking characteristics are respectively indicated in Figs. 6 and 7.

4.2 Main Circuit and Gate Control Circuit

The wiring diagram of main circuit, block diagram and flow chart of gate control are shown in Figs. 8, 9 and 10 respectively.

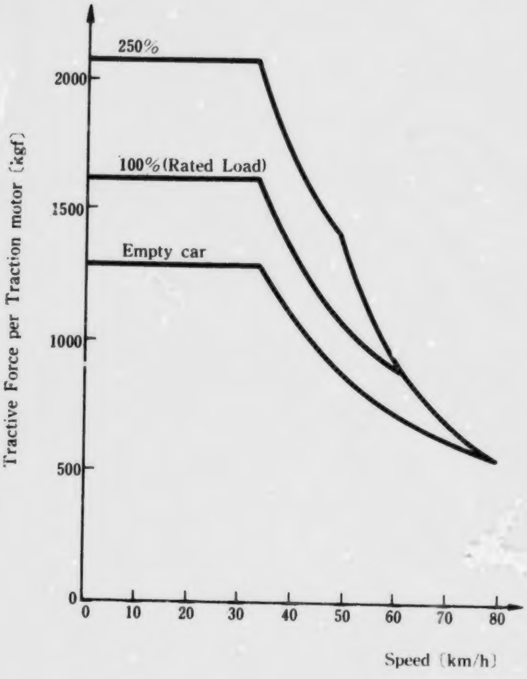


Fig. 6 Powering Characteristics

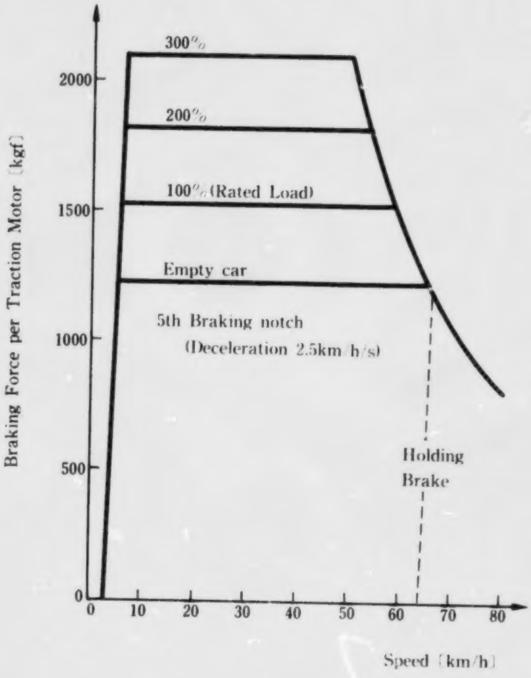
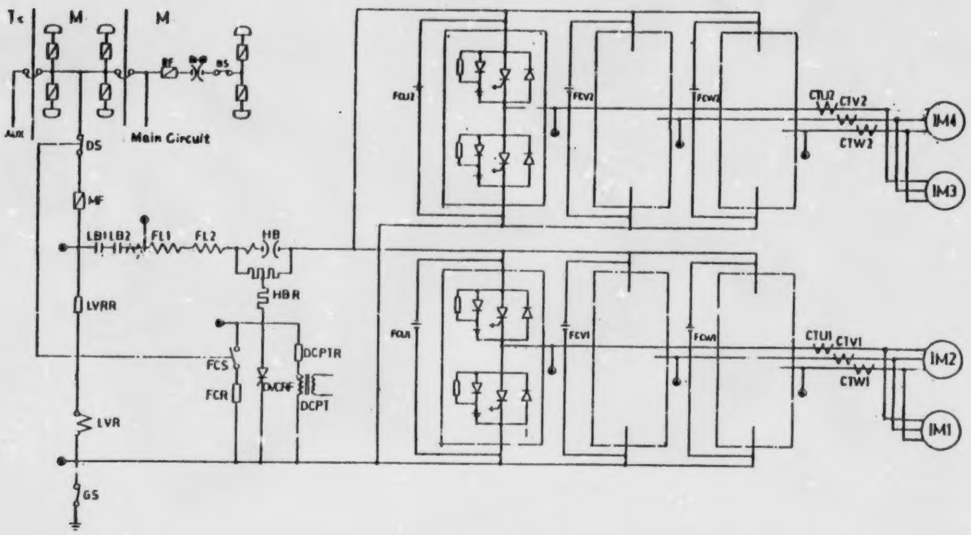


Fig. 7 Regenerative Braking Characteristics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M
BF
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Main Circuit
DS
MF
LB1
LB2
FL1
FL2
HB
HBR
LVRR
FCS
FCR
OVCRF
DCPTR
DCPT
LVR
GS
FCU2
FCV2
FCW2
CTU2
CTV2
CTW2
IM4
IM3
FCU1
FCV1
FCW1
CTU1
CTV1
CTW1
IM2
IM1

Fig. 8 Schematic Diagram of Main Circuit

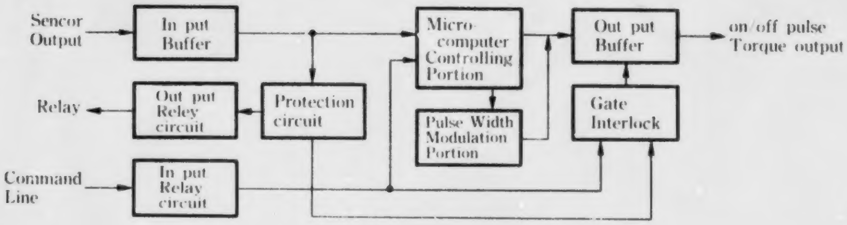
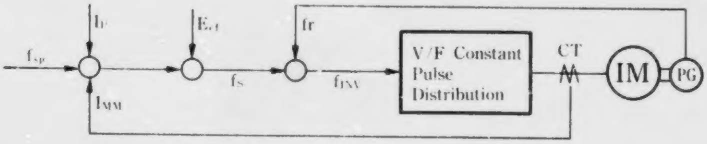

Sencor Output
In put Buffer
Micro-computer Controlling Portion
Out put Buffer
on/off pulse
Torque output
Relay
Out put Reley circuit
Protection circuit
Pulse Width Modulation Portion
Gate Interlock
Command Line
In put Relay circuit

Fig. 9. Block Diagram of Gate Control Circuit


f_{sp}
I_P
I_{MM}
E_{cf}
f_s
fr
f_{INV}
V/F Constant Pulse Distribution
CT
IM
PG

fs: Slip Frequency, fsp: Slip Frequency Pattern.
f_{INV}: Inverter Frequcney I_P: Current Pattern.
Ecf: Voltage of Main Filter Condenser.
fr: Converted Frequency of Traction Motor Revolution

Fig. 10 Flow Chart of Gate Control

4.2.1 Construction of Main Circuit

GTO thyristors are applied to the main circuit. As no commutation circuit is provided in case of this system, commutation capacity is independent of main circuit voltage and commutation noise is almost inaudible.

Since 1S1P connection, which is superior in stability of controlling, is applied to inverter, 2 inverters are connected in parallel and 2 groups are controlled with phase differential. Thus, traction motors are connected to from 2 groups of 1S2P connection.

4.2.2 Construction of Gate Controlling Device

Gate controlling device is constructed with software logic incorporating microprocessor into its principal part. Owing to this construction, the accuracy of controlling has improved furthermore, the applicable range of the device has been expanded, and the optimum control has been made easier to execute.

Its construction is roughly divided into 2 parts, that is the controlling portion with microcomputer, principally composed of microprocessor and memory, and the rest. The former is separated into microcomputer portion and pulse width modulator portion. While the latter, or the rest, is classified into input-output relay circuit, input-output buffer circuit, gate interlocking circuit and protection circuit.

In the microcomputer portion, processing and operation is performed in response to various commands and the output of sensors and in accordance with the patterns stored in memory. Based on the results thus obtained, the pulse width modulator and then inverter gate circuit are controlled.

The principal parts of protection circuit and interlocking circuit are located outside of the controlling portion with microcomputer, so as to enable constant monitoring or interlocking irrespective of the situation of various processing and operation.

4.2.3 Flow Chart of Gate Control

Utilizing the characteristics of numerical control by microprocessor and adopting frequency as major control element, quasi-feed-forward controlling is performed.

Though damping is applied together with the feeding-back of output current and with the monitoring of the voltage at filter condenser to further stabilize the control system, the damping is maintained not to exceed necessary and the minimum limit.

4.3 Major Controlling Equipment

4.3.1 Inverter Equipment

To perform differential control of 2 groups of GTO thyristors connected 1S1P, 2 sets of inverter equipment are provided to a motor car. As filter condensers are divided so as to be contained in inverter box, cable connection between inverter equipment became indispensable. Accordingly, sealed cable is used for this connection to achieve the electrical unification of 2 inverters.

The inner composition of the inverter equipment is as follows. The element in main circuit are contained in the box being divided into 3 pieces. Anode reactor and others are arranged at the upper part of the box. By doing so, maintenance free and prevention of inductive interference are intended for.

4.3.2 Gate Control Deive

To control the gates of 2 inverters, a box for gate control device is provided separately. The device is designed for compactness, high performance, and maintenance free by application of such latest technology as microprocessor.

4.3.3 Filter Reactor

Filter reactor is of hollow and self-cooling type. The application of self-cooling type promoted maintenance free, less noise, and energy saving by not having blower, though slight difficulty is found in furnishing to car.

4.3.4 Line Breaker Box

In this inverter system, the only duty imposed on the line breaker is to disconnect input side of inverter from feeder line, and so necessary and the minimum number of line breakers are required. Therefore, the minimum composition of 2 unit switches and 1 high speed breaker was adopted. In addition, as smaller and lighter equipment than the conventional model are utilized, considerable reduction in size and weight of the box itself is attained.

4.3.5 Bus Line Breaker

Aiming at efficient utilization of regenerative braking force, a bus is laid all along the car. Bus line breaker is inserted in the bus circuit to lessen the ill effect on feeder system. This breaker is as well a compact and light high speed breaker.

Table 3 Outline of Prototype Car

Item	Principal Specifications
Train Composition	Tc M T M M Tc
Passenger Accommodation	End Car: 130 Intermediate Car: 140
Power Supply System	DC 750V, 3rd Rail, Upper Surface Collection
Rail Gauge	1,435 mm
Car Weight	M Car: 35t, Tc Car: 31t, T Car: 24t
Principal Performance	Linear Acceleration: 2.5 Km/h/s
	Deceleration Regular Max.: 3.5 Km/h/s
	Emergency : 4.5 Km/h/s
	Max. Running Speed: 70 Km/h
Dimension (L x W x H)	End Car: 18,900x2,890x3,745 (mm) Intermediate Car: 18,700x2,890x 3,745 (mm)
Body Material	Aluminum Alloy, Entirely Large-sized Extruded Shape
Traction Motor	140kW x 4/car
Control System	VVVF Inverter Controlling
Brake System	Electrical Command Type Electromagnetic Straight Air Brake Combined with Regenerative Brake

Table 4 Major Items of Inverter Equipment

Item	Description
Power Source Voltage	DC 750V
Control System	Automatic Acceleration/Deceleration Control with VVVF Inverter, Regenerative Brake (Combined with Air Brake) with Speed Holding Brake
Traction Motor	3 Phase Cage Type Induction Motor 140kW, 550V, 190A, 55Hz 1,600r.p.m., 750kg with Revolution Detector
Inverter	1. Rated Capacity 680kVA x 2 2. System Voltage Type, Pulse Width Modulation System 3. Powering Control (1) Constant Current, Constant Slip Frequency Control (2) Constant Voltage, Constant Output Control (3) Constant Slip Frequency Control 4. Regenerative Braking Control (1) Constant Slip Frequency Control (2) Constant Voltage, Constant Torque Control (3) Constant Current, Constant Slip Frequency Control 5. Current Control Mean Value Control System 6. Starting System Soft Starting System in which Current is Controlled by Modulation Ratio Control with Fixed Slip Frequency 7. Main Circuit Cutout System Regular: Current Limiting Cutout by Inverter Emergency: Single Step Current Limiting Cutout by High Speed Breaker

Table 4 Continued

Item	Description
	8. Main Circuit System GTO Thyristor System (1S1P, 6 Arm, 2 Group, Parallel) 9. Rating of GTO Element 2,500V, 2,000A (Max. Controllable) 10. Frequency Range 2 - 130 Hz 11. Protective Functions Input Overcurrent, Voltage Drop of Control Source, Traction Motor Overcurrent, Commutation Failure, Unbalance of 3 Phases, Microcomputer Failure, Detection of Excessive Regenerative Braking Force, Temperature Rise of Freon Liquid, Detection of Slipping, Grounding of 3rd Lail , Filter Condenser Overvoltage, Detection of Excessively Low Voltage
Filter	1. Type Reverse L Type Filter 2. Constants Reactor: 8mH (4mH x 2) Condenser: 12,000 μF (2,000 μF x 6) 3. Resonance Frequency 16 Hz

5. Conclusion

The status of the controlling by means of VVVF inverter viewed from the Osaka City is described hereinabove. Responding to the increasing request for high reliability, energy saving, and maintenance free directed to electric railroads, the VVVF controlling systems has a good chance of realization.

The inverter controlling equipment of the prototype cars of the Osaka Municipal Subway System are manufactured by Hitachi, Toshiba and Mitsubishi, the top three manufacturers in Japan, incorporating their essence of electronic technology, and we believe that the equipment are on the highest level in the world. And we expect eagerly that our prototype cars will contribute to the development and propagation of the inverter controlled electric car not only in Japan but also worldwide.

We, at the Osaka Municipal Transportation Bureau, are, based on the operation results of the prototype cars, intending to establish the design criteria for mass-produced cars and to increase the number of the inverter cars in our fleet.

Reference

1. Osaka Municipal Transportation Bureau: "Test Report with Real Car on Induction Motor and Control Equipment with VVVF Inverter", (1982).

OPERATIONAL EXPERIENCES WITH AC DRIVES IN THE FEDERAL REPUBLIC OF GERMANY

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Berlin Transit Authority

Karl Dreimann
AEG-Telefunken
West Germany

This paper gives an account of the experiences made with three-phase drive technology on rapid transit vehicles; main-line vehicles of the German Federal Railways based on the same AC propulsion technology will not be dealt with. The vehicles in question are operating on different metro or light rail systems and are exclusisely supplied with direct current through a third rail or a contact wire at nominal voltages of 750 V or 600 V.

Provided there is signaling equipment on the lines, different systems can be encountered: 50 Hz track circuits, audio frequency track circuits and axle counter circuits. They also comprise lines with automatic train operation.

In Germany and Austria the following cities have already running rapid transit vehicles using three-phase AC drives.

Berlin	(metro)
Düsseldorf	(light rail)
Hamburg	(metro)
Mülheim/Ruhr	(light rail)
Munich	(metro)
Nürnberg	(metro and tram)
Vienna	(metro)

2. Reasons for introducing three-phase drive technology

After the positive results achieved by DC chopper technology on rapid transit vehicles and its large-scale series application, during the first half of the seventies work began on utilizing three-phase propulsion technology offering further advantages beyond those of the DC chopper technology to the user.

Altogether the following points were decisive for changing to these new techniques:

- reduced energy consumption as losses are avoided in the resistors during starting, and braking energy is fed back to the line by regenerative braking. This does not only cut costs but it also reduces problems due to the heating up of tunnels,

- reduced expenditures on maintenance and repairs
The AC traction motors require less wearing parts such as collectors and carbon brushes. In the control the number of electromechanical contactors switching current on and off has been decreased. This reduces the wear on the contacts and welding together of contacts becomes less likely,

- increased riding comfort and higher spot braking accuracy - particularly when operating automatically - by stepless starting and braking effort control.

- reduced slipping and skidding during starting and braking,

- reduced load on the auxiliary converter due to smaller brake exciter requirement. Compared to separately excited dynamic braking of DC traction motors with AC drives, weight can be saved at the auxiliary converter because its rating can be decreased.

- reduced rim wear due to single-axle drive
For conventional vehicles, the DC traction motors longitudinally arranged within the bogie - DUEWAG-type - driving both axles yielded considerable advantages on account of both the simpler electric circuitry (four instead of eight motors in one twin motor coach) and less weight. Disadvantages were a higher wear on rims and flanges because of the mechanical coupling of the axles, and a higher noise level caused by slip stick processes in curves. With three-phase motors of equal output being smaller, it is possible to accomodate two separated motors within the same space (still longitudinally arranged and driving through rectangular transmission gears with low noise generation) and, thus, decouple the axles. As to the circuitry it is of no significance (at a given total output) how many motors are connected to a "bus bar of a vehicle",

- either the bogies can be equipped with a higher motor output, the mounting space remaining the same, or the output is maintained, the bogies become smaller and this in turn results in more space beneath the car body available for mounting the electrical equipment.

- control at any desired constant speed. Due to the motor characteristics, cam-controlled DC vehicles can maintain a desired constant speed only in exceptional cases whereas the current and frequency control of three-phase drives permits to set and maintain any desired torque-speed point below the motor characteristic. This way the behaviour of the trains during operation can be improved and the driver can be relieved in his work.

We don't want to conceal the fact that three-phase propulsion technology has, besides the above mentioned advantages, some disadvantages:

- more mounting space required and higher weight

An important factor is in this connection the line filter mainly serving to smooth the line current. Based on the specific operational requirements, it has to be determined which minimum size is still justifiable. Wherever it has so far been applied on lines with signaling equipment, the danger of disturbing signaling equipment turned out to be smaller than expected on the basis of theoretical calculations, particularly when it is so much harder to reach a critical level as additional interlocks have been built into the signal system, e.g. application of auxiliary voltages of defined phasing in the signaling relays, signal sequence interlocks etc. However, this question has to be carefully analyzed.

- Higher investment costs

Expenditures on power and control electronics of three-phase converters result in higher investment costs for the vehicles, but they can be completely or at least partly offset by savings in operational energy costs. As further series production is continuously improving three-phase propulsion technology, leading to its standardization, the difference in costs between conventional cam or chopper-controlled vehicles and those using the new technology will certainly be reduced.

Fig. 1 Metro twin motor coach F 97.3 with three-phase drive technology of the Berlin Transit Authority (BVG)

- However, it also has to be taken into account that

the Metro's twin motor coaches have been provided with only one cam controller each, the failure of which would leave the unit crippled, i.e. it could not continue its travelling by its own means whereas most of the three-phase vehicles contain two independently working equipments. On failure of one equipment the unit is able to continue service, although only at half of its power.

- Trouble-shooting in workshops more difficult

It will always be a problem for the workshop to rapidly find and eliminate such faults which sporadically occur in service, and this problem can only be solved in a satisfactory way by installing fault detecting and recording equipment. Applying microcomputer technology can be of decisive help, trials are already underway and a number of vehicles has already been equipped with microcomputer control.

In addition to this it is also necessary to adapt the maintenance systems of the workshops to this new technology, because preventive maintenance, as in the case of electromechanical components, cannot be carried out with respect to electronic systems.

From 1975 to 1978 the Association of Public Transit Authorities (VÖV) in Germany and qualified suppliers jointly executed a research project dealing with the effects of DC chopper and three-phase propulsion technology. The project was funded by the Federal Ministry of Research and Technology and particularly went into the problems concerning energy savings and compatibility with other subsystems, e.g. signaling systems, information transmission equipment and power supply installations. These investigations yielded only favourable results and this has been a decisive factor to advance the development and application of these techniques.

3. Three-phase propulsion systems and their testing

In Germany all kinds of three-phase propulsion systems which appeared to be suitable for rapid transit vehicles were being developed and afterwards tested under full-scale operational conditions on prototype vehicles. Basically, the induction-type traction motors may be fed from the three-phase converters having a voltage-impressed or current-impressed intermediate link.

The pulse-width-modulated inverter requires an impressed DC voltage at its input; it converts this voltage into a three-phase system of variable voltage and variable frequency within one single power converter. That is why it can be directly operated at the contact wire. This system was tested by AEG-TELEFUNKEN in cooperation with the BVG on one metro twin motor coach (1976-1978). This vehicle was equipped with a

For details concerning the function of the current-impressed propulsion system, please refer to Dr. Weigel's paper on the subject of "AC Drives for Rapid Transit Systems German Development and Operating Experience", session 7A.

4. Series vehicles in revenue service

4.1 Light rail vehicles of the Rhine Railway Corporation (RBG) Düsseldorf

Following the design of the B80 type vehicles, the RBG and Waggonfabrik Uerdingen AG (DUEWAG) jointly developed the mechanical part whereas BBC Brown, Boveri & Cie AG, Siemens AG and Kiepe Elektrik jointly developed the electrical part. AEG-TELEFUNKEN supplied some components. 12 vehicles have been in service since October 1981, all of them six-axle articulated cars having two motored bogies and one unpowered bogie, their main technical data:

Length over couplers	28 000 mm
Car width	2 650 mm
Seating capacity	72
Standing capacity at 4 standees per m²	106
Tare weight	41 000 kg
Continuous rating of motor	2 x 220 kW
Line voltage	600/750 V

Trains may consist of a maximum of four vehicles.

The cars have been equipped with SIMOTRAC type drives. Each traction motor has been assigned a converter consisting of DC chopper, phase sequencing inverter and smoothing reactor in the intermediate link. The DC chopper works at a constant frequency of 250 Hz, the inverter at variable frequencies of 0.5 to 180 Hz. The firing sequence in the inverters determines the direction of rotation of the traction motors.

Some of the vehicles run on lines equipped with audio frequency track circuits. Since being in service they have been covering a total distance of more than one million vehicle kilometres.

4.2 Metro twin motor coaches of the Munich Transit Authority (VBM)

Six of the VBM's metro twin motor coaches have three-phase propulsion. Their mechanical and electrical main data correspond almost completely with those of the Nürnberg vehicles described under 4.4. The car bodies and bogies were supplied by Maschinenfabrik Augsburg Nürnberg AG (MAN), and the electrical equipment by a joint venture formed by Brown, Boveri & Cie AG (BBC) and Siemens AG.

Deviating from the cars of the VAG Nürnberg, integral construction of extruded alloy profiles was adopted for building the underframe. Traction motors and gears have been designed as SIMOTRAC-D-drive having divided rotors.

Three twin cars have already been in service for a longer period of time, the other three sets are utilized to perform extensive measurements and investigations in order to obtain further knowledge for future series. The vehicles cannot be coupled to the existing direct-current cars so that the advantages of the three-phase propulsion can be completely exploited.

4.3 Metro twin motor coaches of the Berlin Transit Authority (BVG)

Subsequent to a vehicle series of 37 twin motor coaches with cam controller, the Berlin Transit Authority (BVG) ordered six twin motor coaches series F79.3 with the standardized current-impressed three-phase drive. The car bodies and bogies were built by Orenstein und Koppel (Berlin), and AEG-TELEFUNKEN and Siemens AG supplied the electrical equipment for three units each. The vehicles are twin motor coach units, all the axles of which are driven.

Length of one twin car over couplers	32 100 mm
Car width	2 650 mm
Maximum speed	80 km/h
Seating capacity	72
Standing capacity	160
Tare weight	42 800 kg
Motor output (continuous)	8 x 89 kW
Converter rating (continuous)	530 kVA
Line voltage	750 V

Each vehicle contains two longitudinally arranged three-phase motors per bogie, both sharing one housing. The axle distance is 1800 mm which means that this distance is 100 mm shorter than that of vehicles having direct-current motors. The cars equipped by Siemens AG have an integrated motor-gear arrangement (SIMOTRAC); in this case the motor and both gears are combined in one block. One of AEG's cars has also been equipped with integrated motor-gear. As compared with conventional direct-current drives, the weight could be reduced by about 200 kg per bogie.

As the three-phase cars can be coupled to the direct-current vehicles, the DC motor characteristics are automatically simulated at the AC cars while running in combined service. The more favourable characteristics of the three-phase motors become effective when the service is exclusively based on three-phase operation. Each car has one converter feeding the four induction motors connected in parallel.

The vehicles were supplied in the first half of 1981 and, having passed extensive measurements and test runs, they were put into service between October 1981 and June 1982. Up to date they have been covering distances ranging from 40 000 to 140 000 km, the total kilometric performance being just over 1 million kilometers (as of September 30, 1983).

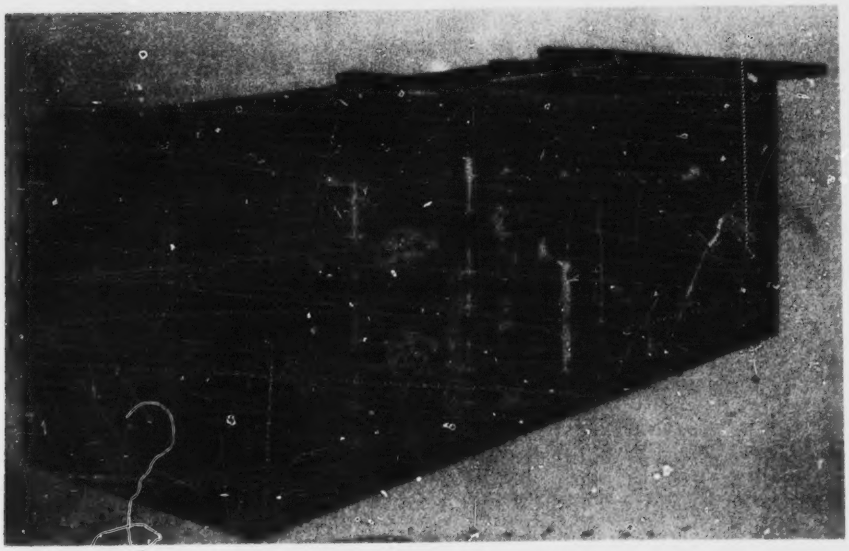

Fig. 3:
DC three-phase inverter with phase sequencing inverter and DC chopper control for 750 V DC, 500 V AC - 600 A - 185 Hz

Having surmounted some initial problems, particularly in the field of control electronics components, reactors, contactors and traction motors, the vehicles nowadays show a satisfactory reliability during service. During the last six months the kilometric performance was 90 % of that achieved by direct-current vehicles operating on the same line. The difference of 10 % was either due to faults in the three-phase equipment or in the conventional part, or to measurement and demonstration runs.

In order to exclude the vehicles disturbing the 50 Hz track circuit of the signaling system, they have been equipped with 50 Hz monitors which are either working redundantly or at fail-safe technique. In case the 50 Hz content of the line current exceeds a value of 1 A for approx. 750 ms, the equipment of the vehicle will be switched off. This happens an average of 1 or 2 times a day per vehicle; so far the faults could never be attributed to the three-phase equipment. They were either caused by load disconnections or voltage jumps on the third rail. Comparative measurements carried out on direct-current vehicles under the same conditions showed that the response values are exceeded more frequently because there is no line filter, yet no critical status ensues.

Due to regenerative braking, 25 % to 30 % of the current input is returned to the line; measured at the current collector. The power supply sections are connected through. As the three-phase vehicles have a higher weight, they consume 8 % more energy during starting than a comparable direct-current vehicle.

4.4 Metro twin motor coaches of the Nürnberg Transit Corporation (VAG)

Based on many years of experience gained with a street car using three-phase propulsion technology, the VAG ordered a series of 22 metro twin vehicles which were commissioned from April 1981 to December 1982 (suppliers: MAN and Siemens). The outside resembles to that of the direct-current vehicles having already been in service over a longer period of time, and they can be coupled to any other car. Until September 1983 they had been running over 2 million km.

Length over couplers of the twin unit	37 150 mm
Car width	2 900 mm
Maximum speed	80 km/h
Seating capacity	98
Standing capacity	192
Tare weight	53 500 kg
Motor output (continuous)	4 x 195 kW
Third rail voltage	750 V
Converter capacity (cont.)	3 x 936 A

The Nürnberg three-phase cars too have a SIMOTRAC drive with the integrated traction motor-gear block, in this case, however, without divided motor.

According to the standard circuitry, the electrical power circuit consists of one DC chopper with phase-sequencing inverter for both traction motors of one single car, the line filter is common for both cars. The drive is controlled in accordance with the transvector principle.

In order to exclude disturbances of the signaling equipment, the cars were equipped with 50 Hz monitors as well.

In order to increase the reliability and availability of the vehicles, a fault reporting system is adopted, indicating faults to the driver and classifying them at the same time. Thus it is easier to reach a decision on whether and how long the faulty vehicle can still continue to operate. The fault is also stored

PWM inverter supplying the 8 traction motors of the twin unit. The installed motor rating amounted to a total of 8 x 70 kW.

In order to keep line voltage variations from the inverter, a DC chopper may be inserted at the line side. Made by Brown, Boveri & Cie, it was designed for the prototype vehicle of the Hamburg Hochbahn AG as a voltage chopper in cross arrangement. It increases the variable third-rail line voltage to a steady value of the intermediate link voltage. The prototype vehicle was tested from 1979 to 1981. It is a three-car motor coach having a tare weight of 50 t and a maximum speed of 80 km/h. The three-car set contained 2 converter equipments, each of them supplying 3 traction motors of a total output of 360 kW.

The current-impressed propulsion system comprises at its input a DC chopper, an intermediate link with reactor choke and an inverter with phase sequencing commutation. Siemens tested this system on a Nürnberg street car (1976 - 1978) equipped with one converter and one traction motor with a rating of 185 kW.

One of the metro twin motor coaches in Vienna was fitted by Siemens with a complete prototype equipment of the current-impressed propulsion system. In this case, each car had a converter of its own in order to supply the two tractions motors connected in parallel. The tare weight of this vehicle was 55 t, the maximum speed 80 km/h, the total output of the 4 traction motors of the twin unit 4 x 200 kW. In the case of the light-rail cars, Siemens tested the current-impressed three-phase propulsion system in Mülheim. This articulated vehicle had a tare weight of 29 t, a maximum speed of 70 km/h and a motor output of 2 x 190 kW. At the Hamburg Metro, BBC equipped another three-car set in order to test a prototype of the current-impressed propulsion system.

All prototype vehicles of the three-phase propulsion systems tested have a combined regenerative and dynamic brake. The highest possible amount of braking energy is regenerated to the line and only when the line is less receptive a part of it is fed to the brake resistors. In all these cases dynamic braking is independent of the line voltage. This is required according to German law in order to guarantee that, provided no braking energy can be returned to the line, the two braking systems - the electrical and the pneumatic brake - continue to function.

After thorough investigations and successful tests on the propulsion systems under all service requirements, the Association of Public Transit Authorities and industry jointly layed down a uniform system as standard.
For this reason transit authorities are not restricted when they place orders for components for their equipments with an electric company. This also assures complete compatibility among the manufactures. The current-impressed propulsion system was selected because it requires the least sophistication in the power electronics of the converter and in the control electronics. The functions of inverting and voltage controlling of the current-impressed three-phase system are very clearly arranged, the phase sequencing inverter is of particularly simple commutation circuitry.

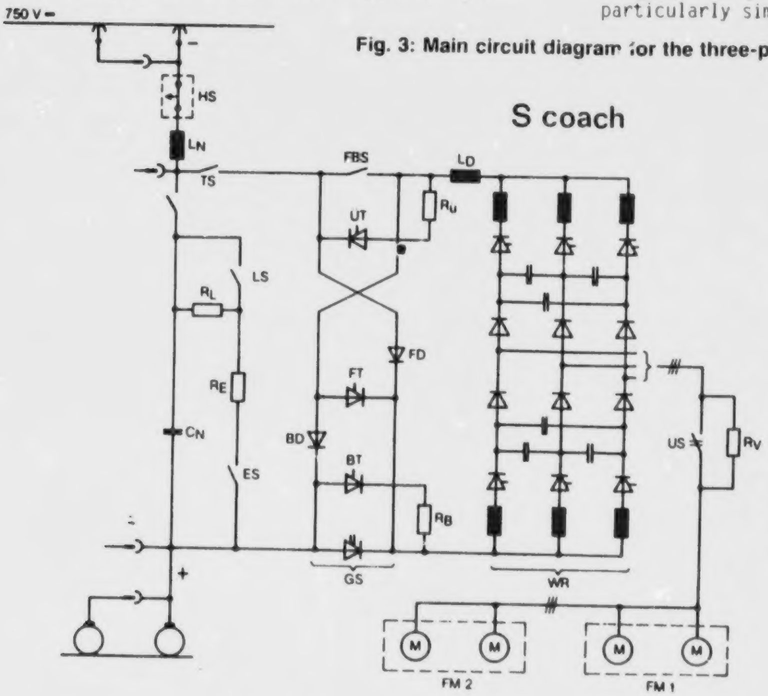

Fig. 3: Main circuit diagram for the three-phase motor coach F79.3 of BVG

HS = main circuitbreaker
L_D = intermediate link choke
L_N = grid choke
R_V = braking series resistance
US = bridging contactor
UT = bridging thyristor
WR = phase sequencing inverter
R_B = braking resistance
R_E = discharge resistance
R_L = charging resistance
R_C = bridging resistance
FD = free-wheel diode
FT = free-wheel thyristor
GS = d. c. chopper control
BD = brake diode
BT = brake thyristor
C_N = grid condenser
ES = discharge contactor
FBS = running-braking contactor
FM 1-4 = twin traction motor 1-4
LS = condenser contactor

so that it can be read off by the staff. Tests are being carried out on two cars in order to detect and record the limiting operational conditions upon a failure by means of an MC fault memory.

As compared with direct-current trains, the savings in energy recorded in Nürnberg amount to about 25 %, 16 % of which are braking energy directly returned to the line. This value is relatively low because the no-load voltage of the substations has not been decreased from the upper limit. This corresponds almost exactly with the value ascertained for these conditions by the research project of the VÖV.

5. General operating experience

Despite the fact that the vehicles described in this paper differ with respect to mechanical construction and electrical equipment and show remarkable differences in their traffic systems and service conditions, in many respects the operating experiences can, nevertheless, be reduced to a common denomihator. On the basis of all the services carried out so far some generally valid statements can be made.

Compared with conventional vehicles of mature technology, the availability of the vehicles is considerably restricted at the beginning. This results from longer commissioning periods and initial difficulties which are due to component faults and problems of integrating electronic and electromechanical processes and heat dissipation. But this may also be caused by exaggerated requirements on the monitoring equipment which had at first appeared to be absolutely necessary for testing purposes. Generally, those difficulties can be solved after rather short periods in service and the availability is about the same as that of the other vehicles. However, it is a prerequisite that both manufacturer and operator spare no effort to locate and eliminate deficiencies.

The savings in energy achieved correspond with those previously determined in separate tests or by theoretical calculations. They vary between 25 and 35 % and are a function of several conditions, such as distances between stops, the difference between maximum braking voltage of the vehicle and no-load line voltage, connection state of the power supply and line system, starting-idling-braking program, especially brake setting speed and head distance of the trains.

The disturbances of signalling equipment of different systems have proved to be less critical than originally expected. As the design period of the protective equipment against critical interference currents was accompanied by thorough theoretical considerations, the equipment met with success. According to our present findings dangerous conditions can be prevented with sufficient security by the dimensioning of the line filter, the installation of 50 Hz monitors and the suppression of critical frequencies by means of circuit design.

The disturbance of subsystems, e.g. loudspeaker and telecommunication equipment, can be prevented by adequante shielding and cable laying, although it cannot be excluded that individual vehicles will be affected by disturbances, the origins of which may sometimes be hard to find and to eliminate.

The noise emission of components with block form currents, e.g. traction motors and reactors, may exceed justifiable limits as long as no measures will be taken against it. Provided the traction motors are adequately designed, the laminated cores of the reactors are sufficiently braced, vibration absorbers are used, the equipment boxes are acoustically enclosed and noise bridges are avoided, it is possible to lower the noise level to such an extent that three-phase vehicles are not louder than those running with direct-current controls. Sometimes there is the subjective impression that the level is higher, but this is due to the emission of other frequencies and in most cases it cannot be proved by objective measurements.

No final data can be given on the amount of maintenance required. It should be expected that it will be reduced since some of the wearing parts at the traction motor can be dispensed with, the number of power-switching contactors is reduced and electromechanical components are replaced by static electronical components. If necessary, the maintenance system has to be reorganized as only functional tests and trouble shouting have to be carried out when adopting electronics whereas a regular preventive maintenance can be dispersed with.

Yet one problem remains to be solved. It takes much too long to locate failures occurring in service and caused by dynamical processes partly resulting from external influences which can hardly be reproduced. In order to remedy this, automatic fault detecting and recording devices can be installed which will be the standard equipment of some of the future vehicles. The necessary qualification of the workshop staff can be achieved by intensive training in cooperation with the supplier companies.

6. Further extension of the rolling stock with three-phase propulsion technology

6.1 39 Metro twin motor coaches BVG (Berlin/West)

At the end of 1981, the Berlin Transit Authority (BVG) ordered another 39 twin coaches with three-phase propulsion equipment (series F84) for the extended metro lines of the city. Their main data corresponds with the data of the vehicles described under 4.3. They are supplied from the end of 1983 until the beginning of 1985.

Compared with the pre-series F79.3 it differs with respect to the supply: car body and bogies will be built by the Waggon-Union (Berlin/Siegen), traction motors and drives (type

SIMOTRAC) by Siemens AG/Thyssen Henschel, the electronic controls and auxiliary converters by AEG-TELEFUNKEN and the power electronics by both electric companies participating. The successful interaction of the components produced by the two manufacturers has been tested in one of the pre-series units.

6.2 10 metro twin motor coaches VAG (Transit Corporation Nürnberg)

In order to complete its rolling stock, the Nürnberg Transit Authority ordered another 10 metro twin motor coaches, the main data of which correspond with those of the vehicles described under 4.4. The first cars are supplied in 1983 and when all of them have been delivered, more than 50 % of the fleet in Nürnberg will be equipped with three-phase propulsion technology.

6.3 24 light rail cars Rheinbahn Corporation (Düsseldorf)

Besides the 12 vehicles already in service the Rheinbahn Corporation Düsseldorf placed an order for a further series of 24 light rail cars. Supply will commence in the middle of 1984.

6.4 Current-impressed three-phase propulsion technology outside Germany

Impressed by the prototypes of the current impressed propulsion systems successfully tested by the German Transit Authorities, the Turin Transit Authority placed an order for electrical equipment for 40 articulated street cars and the Metro Madrid for 6 metro twin motor coaches with AEG-TELEFUNKEN. Supply of the vehicles commenced in October 1983.

7. Technical further development

With respect to the converter power electronic components, the trends of the further development of the three-phase propulsion equipment aim at the employment of gate-turn-off thyristors and freon boiling cooling.

By means of the GTO thyristors the sophistication of the self-commutated converter can be reduced. The number of semiconductor elements is reduced and there are no commutation capacitors. Currently GTO is being used in the turn-off circuit of auxiliary converters and DC choppers on locomotives and rapid transit vehicles. Work on the development of inverters with GTO in the main circuit for the drive converter of traction vehicles is continuing.

The compact design of the converters and the high utilization in conjunction with the good cooling result in a reduction of weight and volume. When all components are accomodated in a sealed tank under boiling freon at the same time, they are intensively cooled and completely protected against environmental influences. Boiling cooling is also used in combination with heat cans. In this case the semiconductors are easily accessible. Both arrangements are being tested on vehicles in Germany.

Further improvements can be achieved in the field of control technique by using microcomputers. In Germany the electric companies developed special microcomputer systems for the specific requirements on board vehicles. They permit a reduction of the volume of the electronical control centers and, therefore, an improved reliability of the complex three-phase drives. More extensive monitoring and fault detecting and reporting systems permit a faster location and analysis of the causes responsible for faults. This increases the availability of the vehicles.

The concentration of extensive control functions in electronic control centers requires a high-capacity data transmission between these electronical equipments. The multiplex data processing of microcomputers and their bus system suggests the use of multiplex data transmission. For this purpose it may be favourable to adopt glass fiber optics which enable the transmission of great amounts of data without any potential connections of different electronic controls and without any EMC problems. This is of great importance because on board the vehicles cabling of the power part with very steep current changes are very close to the control cables.

As the advantages of the power and control electronics have been resolutely utilized in correspondance with the dynamic development of the components, the electrical equipment of German rail vehicles is of high standard and quality. The technical realization of these possibilities and their economical application according to the special requirements of vehicle could only be achieved on the basis of close cooperation between the transit authorities and the supply companies in the course of development, prototype testing and further development for series production.

OPERATIONAL EXPERIENCE OF AN A.C. PROPULSION SYSTEM IN REVENUE SERVICE; THE HELSINKI METRO

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Introduction

The City of Helsinki made a final decision to build a metro or subway system in 1969 to expand the mass transportation system of the city, of which a significant part is and has been for decades carried out by electrically powered transit vehicles such as local mainline railway trains, light rail vehicles and trolleybuses.

The original intention was to provide the new metro cars with the most advanced propulsion system practical at that time, which was the chopper controlled dc system. Six prototype cars with a chopper propulsion system were ordered, and they were delivered to the customer in 1972 among the very first chopper controlled vehicles in the world.

During the lengthy construction period technology was, however, developed further and by the middle of the 70's the propulsion supplier was able to propose a new propulsion system, and after a serious consideration of the advantages and disadvantages of the new system, keeping in mind that the new cars would be in service beyond year 2000, the Rapid Transit Office of Helsinki decided to purchase the new cars equipped with an ac propulsion system. Those cars, called the series M-100, were the first series-ordered ac rapid transit cars in the world.

The reasons for the selection were roughly the same as one can today read in about any transit magazine, mainly:

- reduced need for maintenance because of:
  - simple and rugged, totally enclosed traction motors
  - permanent main circuit with no re-connecting contactors
- low energy consumption because of high efficiency and low losses
- predictably good availability and reliability
- competitive acquisition cost

The first cars were put on track for experimental service in 1977 and the revenue service started on June 1, 1982. The experience gained so far has shown that the selection of the Helsinki metro propulsion system was a wise one.

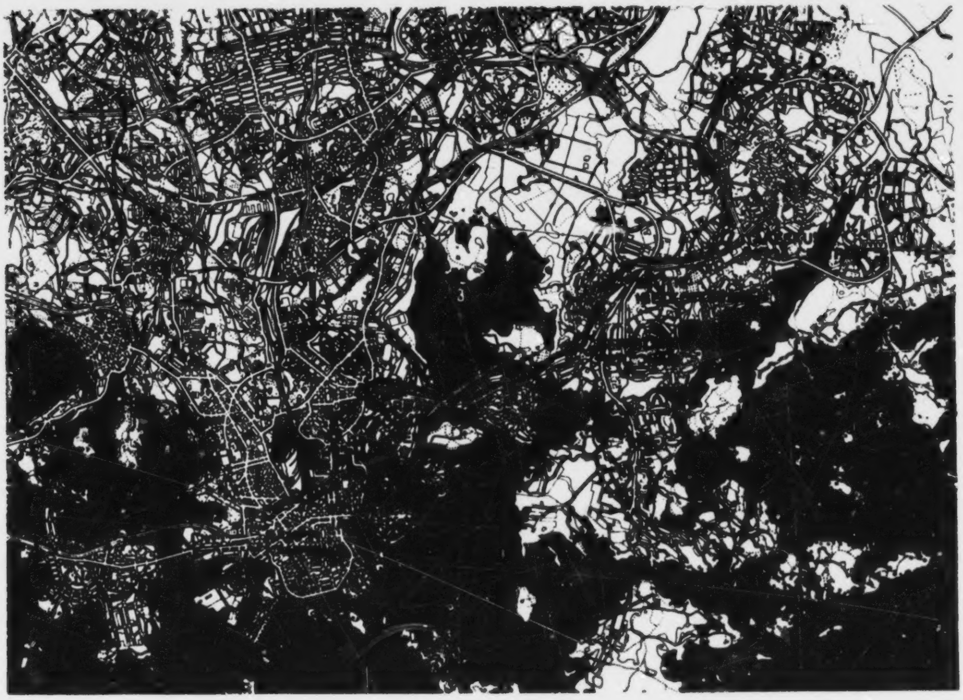

Fig. 1. The Helsinki subway line

1. The Helsinki Metro System

At the moment there is one subway line in Helsinki as shown in Fig. 1. It runs between the peninsular downtown area and eastern suburbs. The length of the line is today 11.2 km (7 miles) double track, of which some 4 km (2.5 miles) is underground and the rest on the surface or elevated. There are 7 stations; the 8th one is to be completed in 1984. The main shop, big enough to take care of the entire fleet of 84 cars, is located near the eastern terminal station.

A 3.3 km (2 miles) expansion to the line, shown with a dashed line in Fig. 1, is under construction. It will be completed in 1986. There will be 2 additional stations. No additional lines have been decided upon at the moment, mainly because of financial reasons, because the city has had to carry all costs alone without any funding from the government.

The City of Helsinki has ordered altogether 42 car pairs, which are the smallest operational units, to carry the estimated number of passengers. Today 35 out of those 42 are in service. The delivery rate is about one car pair in 6 weeks, and the delivery is expected to be completed in early 1985. During rush hours the metro trains run in a configuration of three car pairs coupled together, while during off-peak hours two pairs are usually enough. The headway is 5 minutes during daytime.

The new metro was welcomed fairly favorably by the public, which is proved by a graph of the number of passengers, shown in Fig. 2. Today approx. 95.000 passengers ride the metro daily.

The environmental conditions in Helsinki are very hard. The outside temperature may vary between -30 °C (-22 °F) and +35 °C (+95 °F). In winter the outside part of the track is snow-covered, and snowy and icy conditions are usual in Helsinki. One peculiarity typical to the Helsinki metro are strong environmental shocks in winter because the line runs only partly underground. The ambient air temperature in tunnels is fairly stable, some +10 °C (50 °F) throughout the year, while the outside temperature may go very low and the trains pass this temperature barrier in only a couple of seconds. This, of course, brings with very severe requirements to the equipment.

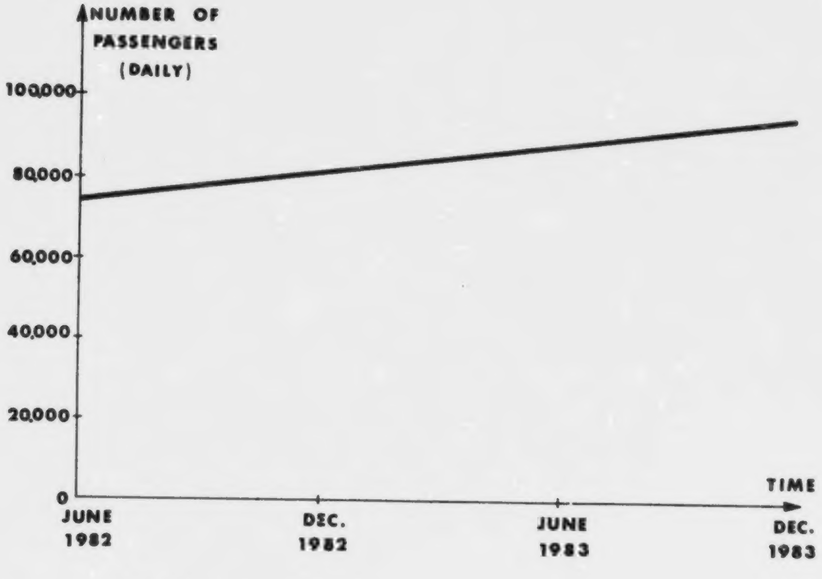

Fig. 2. Number of passengers in the Helsinki Metro

2. Metro Cars

An outline drawing of the Helsinki metro car is shown in Fig. 3. and a photograph in Fig. 4. The cars are of welded aluminium construction with very light weight; the 22-meter (72-feet) car with a capacity of 200 passengers weighs only 30000 kg (66000 lbs).

The propulsion system operates on a 750 V dc third rail supply. The system is on a per truck basis, as shown in Fig. 5., which gives a good redundancy. The Helsinki system is not regenerative, because a careful analysis at the time of the decision did not favor it. The braking energy is used for heating the interior of the cars, which utilizes most of the waste energy for about 7 months per year.

All 8 axles of a car pair are powered with totally enclosed induction traction motors. The two motors of a truck are supplied by a common inverter drive unit, which holds beside the actual PWM inverter also a LC line filter and a braking chopper, which controls the electrodynamic braking.

The power rating of each traction motor is 125 kW. Some other key parameters of the motor are given in Table 1. The inverter drive unit rating is 420 kVA. One traction motor weighs 490 kg (1080 lbs), an inverter drive unit 660 kg (1450 lbs) and the braking resistor unit (common to both truck drives of the car) 520 kg (1150 lbs). Thus the total weight of the ac propulsion system is 3860 kg (8500 lbs) per car, including also the weight of the control electronics.

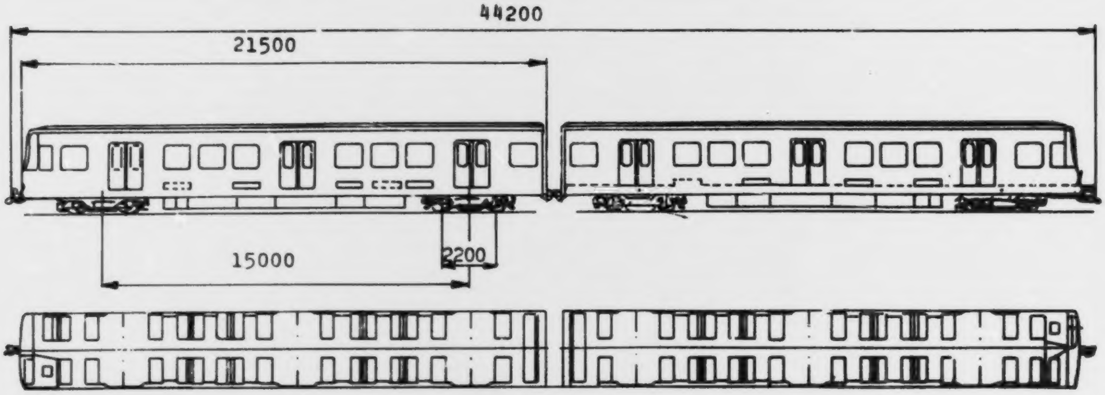

Fig. 3. Outline of the Helsinki Metro car

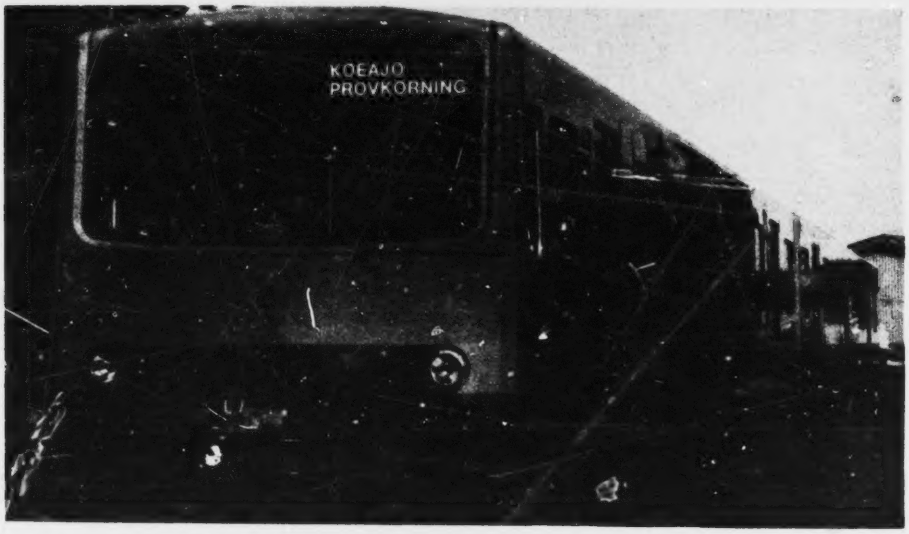

Fig. 4. The Helsinki Metro car

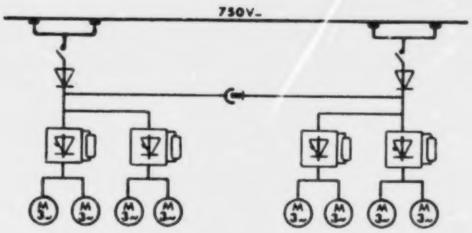

Fig. 5. Block diagram of the ac propulsion system of a car pair

Table 1. Traction motor parameters

- type 3-phase, 4-pole squirrel-cage induction motor	
- rated power	125 kW
- rated voltage	560 V, 3-ph
- voltage range	0 - 700 V
- nominal frequency	68 Hz
- frequency range	0 - 150 Hz
- rated speed	1990 rpm
- speed range	0 - 4500 rpm
- totally enclosed, fan-cooled (TEFC)	
- weight	490 kg (1080 lbs)

A cross-section of the TEFC traction motor is shown in Fig. 6.

3. Service of the metro cars

The City of Helsinki started the metro construction program by building a 3 km- (2 mile-) long test track, which later on was included in the actual line. The test track was completed in 1972. At the same time the 3 prototype car pairs with chopper control were delivered. They were tested on the track for several years.

The first car pair of the new order, with an ac propulsion system, was put into track in summer 1977, and it was followed by two more car pairs before the end of that year. Since then those cars, together with later ones, ran in an experimental service, which consisted of a series of type tests and a lengthy simulated revenue service period. The system was thoroughly tested in all circumstances through all seasons, which offered a good opportunity to debug the propulsion system to overcome all "infant diseases" before the beginning of actual revenue service. Numerous weak points were discovered and corrected so that no big npleasant surprises were presented when the revenue service began in June 1982.

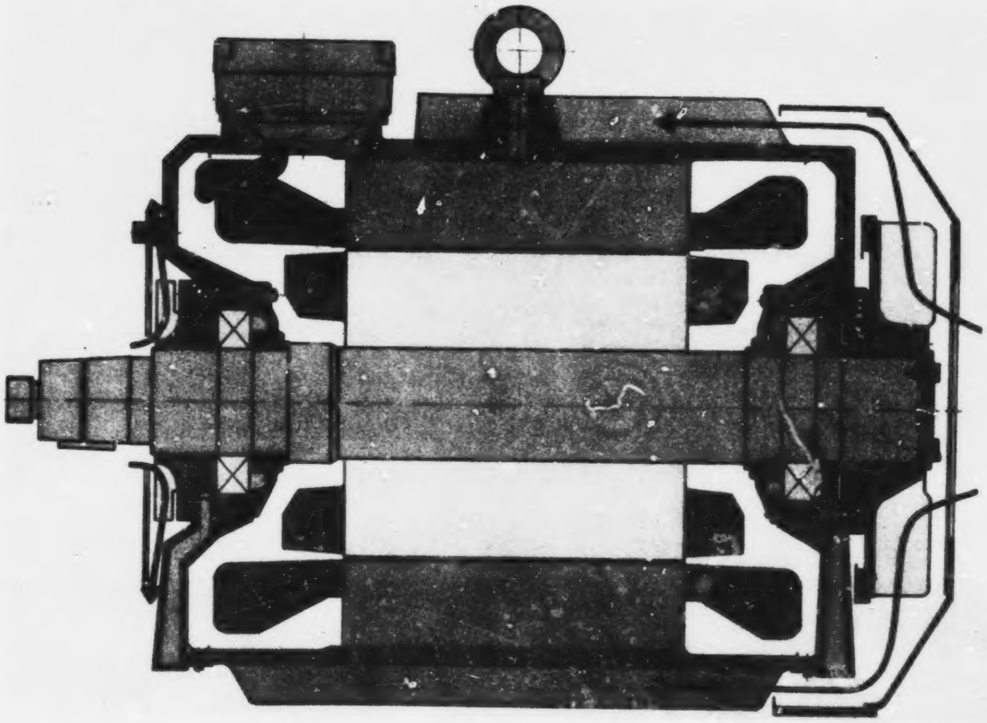

Fig. 6. Cross-section of a TEFC traction motor

At that time there were altogether 18 car pairs, which had run a total of 800.000 car kilometers (500.000 car miles) in the experimental service. At the end of 1983, 19 months later, 35 car pairs were in service and their total mileage was about 9.4 million car kilometers (5.9 million car miles).

As mentioned before, the rest of the cars will be delivered and put into service at a rate of one car pair in six weeks, so that in the beginning of 1985 the whole fleet of 42 car pairs will be running. At the moment the cars accumulate together some 580.000 car kilometers (360.000 car miles) per month. Each car runs approx. 100.000 km (60.000 miles) annually.

4. Reliability

The reliability of the series M-100 metro cars has turned out to be good. Generally the mean times and distances between failures have been long. Especially the ac propulsion system as well as the static auxiliary inverter system used in the new cars have by far exceeded all expectations. The very good reliability figures are partly due to careful engineering, partly to thorough testing and partly to the long experimental service prior to opening of revenue service, which brought into daylight most of the problems before they could become a potential nuisance to the passenger traffic.

As far as the propulsion system (traction motors, inverter drive units, braking resistors and control systems) is concerned, failure rate milestones shown in Table 2. can be given of the revenue service period.

Table 2. Failures during revenue service

Time	Cumulative Distance Miles	Cumulative Distance Kilometers	Cumulative Motor Failures	Cumulative Inverter Failures	Cumulative Control Failures	Total Cumulative Failures
August 31, 82	350.000	560.000	–	1	10	11
November 30, 82	1.250.000	2.010.000	–	5	22	27
February 28, 83	2.000.000	3.200.000	–	9	30	39
May 31, 83	2.890.000	4.650.000	–	12	42	54
August 31, 83	3.870.000	6.230.000	–	17	52	69
November 30, 83	4.940.000	7.950.000	–	20	57	77

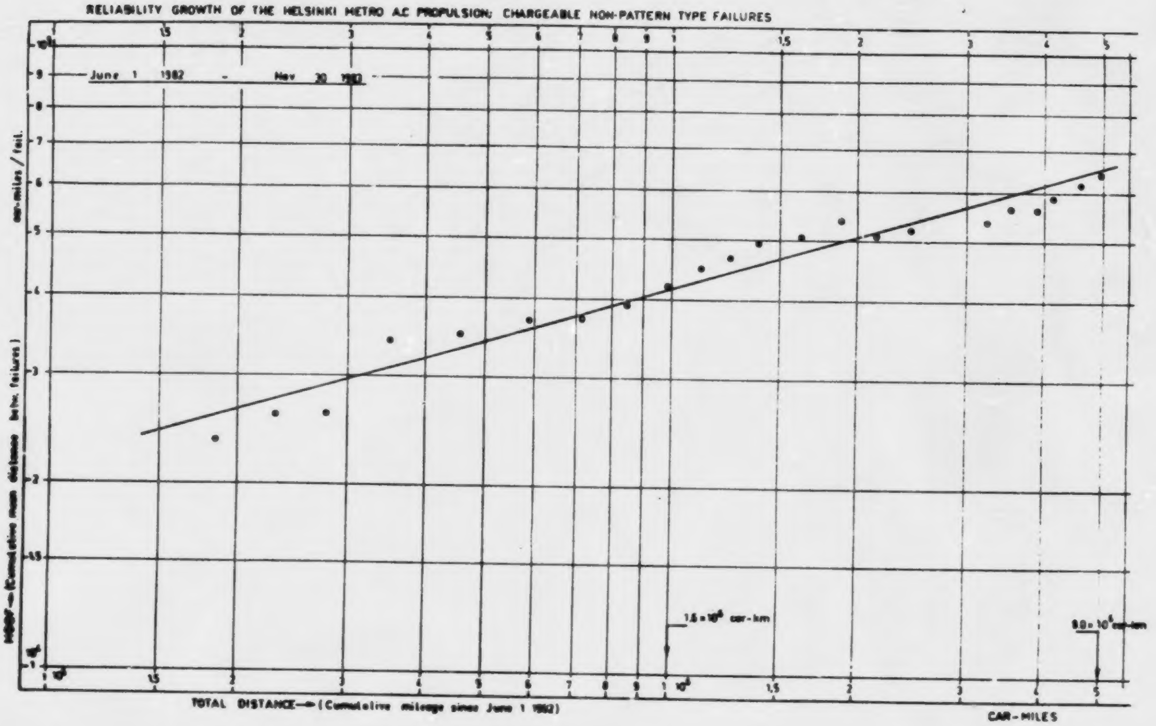

Fig. 7. Cumulative reliability of the Helsinki Metro cars

The same information is given as a graph in Fig. 7. The graph shows that the reliability has improved constantly during revenue service. The mean distance between failures, cumulated during the entire revenue service, was at the end of November 1983 100.000 car kilometers (64.000 car miles), and, as shown in Fig. 7., the figure is still improving so that in fall 1983 the MDBF has been 210.000 km (130.000 miles). According to comments from transit properties both in Europe and the U.S., this reliability is more than satisfactory from the operating point of view.

As shown in Table 2, the majority of propulsion failures originates from the control system, which may also result in main circuit malfunctions. Typical control circuit failures are malfunctions caused by for example defective components or bad connections.

Many inverter failures are also low-level electronic component failures in subassemblies such as gate pulse amplifiers or transducers. A couple of semiconductor failures have been noticed without any evident reason; these failures may be caused simply by weak individual devices. The system has also experienced a few capacitor failures.

The Helsinki metro cars have also a 45 kVA/50 Hz static auxiliary inverter to power the auxiliaries of the cars. There is one auxiliary inverter in a car pair and its construction and operating principle are very much like those of the propulsion inverter. During the revenue service the auxiliary inverters have had altogether 10 failures, which give a total MDBF of 400.000 km (250.000 miles). Also a majority of the auxiliary inverter failures has been on the control boards.

In Helsinki all failures are classified into two categories according to the consequences of the failure:

Category 1 failures:
- detected by a "failure" annunciator or driver's observation of incorrect operation
- car pair is not capable of carrying out service
- car pair is taken out of service and replaced by a spare car pair
- decision of action is made by the driver, regional traffic control or maintenence personnel
- usually all propulsion failures belong to Category 1

Category 2 failures:
- detected by an annunciator or driver's observation
- failure does not affect the service capability
- car pair stays in service until the end of the shift
- Category 2 consists of secondary failures, such as ventilation or lighting failures

The failure figures given above include both Category 1 and Category 2 failures of propulsion system.

Normally a failure in a truck drive or its control will automatically disconnect the defective truck or car from the prime power in order not to interrupt the service of the train but let it continue operation without the performance of the defected truck, which usually does not cause delays. The train can keep its schedule with 25 % of the propulsion systems out. A defective car and its pair are kept in service for two round trips because of heating up of the friction brakes.

The reliability figures given above count normal random-type failures. Some pattern failures with certain detected reasons, which are being or have been corrected by proper action, are excluded. There are three pattern-type failures:

- traction motor insulation failures
- speed sensor failures
- mechanical fuse failures.

The traction motor insulation failures were caused by inadequate impregnation, which resulted in partial discharges in the stator winding and ultimately a ground fault of the motor circuit. After discovering this pattern failure, Strömberg started replacing the motors with repaired ones with a new stator winding with an improved impregnation. At the moment 16 of the 35 car pairs still carry the old motors, 19 have been replaced. No new motors have had insulation problems. All new cars have also new motors.

The subcontractor-supplied speed sensor failures have been caused by manufacturing problems. The sensing electronics are epoxy-potted and the potting has not withstood the hard environmental conditions, especially the thermal shocks, but has cracked. Humidity has reached the electronic circuits through the cracks and caused malfunctions. A new, improved sensor type has been installed after the difficulties during last winter, and failure rates have gone down considerably, although some failures have still been experienced.

The first cars were equipped with main circuit fuses not suitable for the use. As a consequence of cycling currents and mechanical vibration together the fuses failed after a fairly long service. The fuses used after discovering the problem have not caused any trouble. All weak fuses will be replaced.

5. Maintenance

Because of the relatively short revenue service time and the small number of cars in service, the maintenance practices are being established at the time. As a rule the Helsinki metro maintenance personnel reports the ac propulsion system to be easy to maintain. The need for both preventive and corrective maintenance is low.

The preventive maintenance of the propulsion system includes following main steps:

100.000 km (60.000 miles), once a year:
- inverter units:
  - visual inspection
  - cleaning with pressure air
- braking resistor unit:
  - visual inspection
  - cleaning
- traction motors:
  - lubrication of bearings

600.000 km (370.000 miles), every 6 years:
- caused by grinding of wheels
- inverter units:
  - disassembly of subunits
  - thorough cleaning
  - dielectric tests
- control unit:
  - cleaning
  - checking of functions
- traction motors:
  - removal of waste grease

The maintenance steps shown above are required by the propulsion system. The mechanical parts of the cars require more frequent maintenance. The basic intervals are 5000 km (3000 miles), twice a month and 10000 km (6000 miles), once a month. These maintenance steps are mainly visual checkings of bearings, couplings, pneumatic equipment etc.

Estimated manpower requirements for preventive maintenance of the propulsion system are:

100.000 km 3 man days/car pair
600.000 km 15 man days/car pair

The skill level required for preventive maintenance is a skilled craftsman with special training for the metro equipment. The shop supervisor and foremen usually have a technician's education. The Helsinki metro has all necessary facilities and manpower to carry out all steps of preventive maintenance.

The corrective maintenance is mainly repair work within the electronic part (i.e. inverter drive units and control unit) of the propulsion system. The braking resistors and traction motors have turned out to be very reliable after the "infant disease" insulation problem of the motors was solved.

To make maintenance as easy as possible the electronic units have a modular construction with distinctive and easily removable subassemblies. In the control unit the circuits are laid on printed circuit boards, which are very easy to replace. Also a complete control rack can be easily replaced. The inverter drive unit contains subassemblies such as one-phase power modules, commutating modules, braking chopper power modules, gate pulse amplifiers or line inductor. Fig. 8 shows a principal layout drawing of the inverter drive unit with major subassemblies. A photograph of the unit is in Fig. 9.

Some actually experienced replacement times of subassemblies are:

- control board 2 - 3 min.
- power module 1 hour
- commutating module 1 hour
- pulse amplifier 1 hour

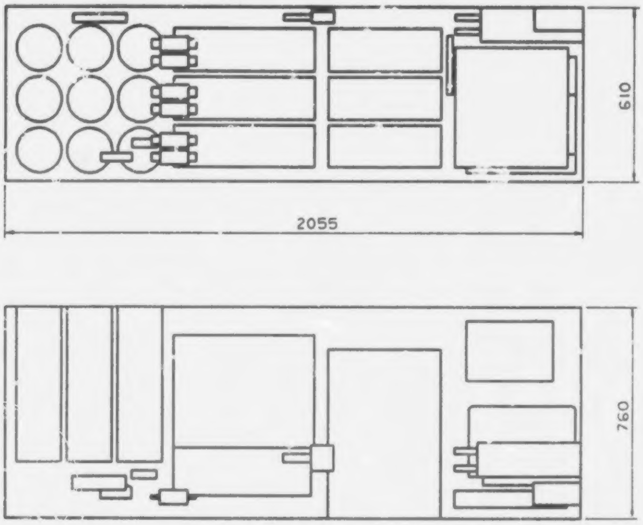

Fig. 8. Layout of an inverter drive unit

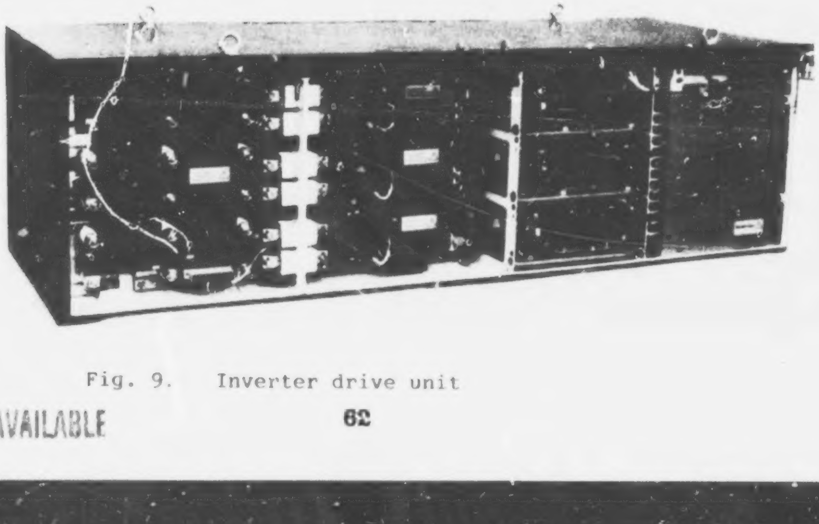

Fig. 9. Inverter drive unit

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Most subassembly replacements are possible without having to remove the unit from the car. The inverter subunits are accessible from the side of the undercar, all control electronics are in a cabinet inside the car so that the control boards can be reached from the cabinet door.

Usually repair work is done in the repair shop. A defective subunit is removed from the car and replaced by another. The failed unit is then repaired in the electronic department of the shop, and the repair time does not delay the car's return back to service.

Usually, however, the main problem in repairing electronic units is not the actual repair work but to find out what has failed, in other words troubleshooting. For that purpose the system is provided with annunciators, which tell the driver if something goes wrong, and what action is required to isolate the fault. In addition the control boards are provided with failure LED's, which show the cause of a failure. The system is provided with a first-event memory to show the origin of a failure event chain. Also the boards are provided with test pins to connect external test equipment without having to remove the board to find out the failure in case the LED information is not sufficient. An external main circuit simulator can also be plugged into the control system to simulate interface with the power circuit instead of having the main power on.

In most cases a main circuit failure is indicated by a blown fuse. The origin of the failure chain can then be found following a detailed step-by step troubleshooting procedure, which leads to a defective component or subassembly to be replaced. One of the most common reasons for blown fuses is a short-circuited power semiconductor, easily located merely with an ohmmeter.

Because the troubleshooting methods of the system used in the Helsinki metro are not as advanced as in more recent systems, the skill level requirement for the personnel is fairly high. The transit property uses mainly technicians who are in addition very familiar with the system. Also specially trained craftsmen are used for troubleshooting. In more advanced, later-generation ac propulsion systems the control system has a fairly wide self-diagnostic capability and an effective interface with automatic external test equipment, both of which factors reduce considerably the need for highly skilled personnel for troubleshooting.

Generally speaking the skill level required for troubleshooting an ac propulsion system is equal with the one for dc systems. The Helsinki City Transport has experience on both of them, because they operate, in addition to the ac rapid transit cars, also a fleet of chopper-controlled light rail vehicles.

The Helsinki metro has experienced following typical troubleshooting times:

- control board 1 hour
- power module 0.5 hours
- transducer 1 hour

If the system fails during the warranty period, the manufacturer takes care of troubleshooting. The first cars have been out of warranty since summer 1983, and today 27 out of the 35 operating car pairs are on the responsibility of the transit property, and they are kept in operating condition by the property personnel.

6. Availability

At the time of ordering the rolling stock the Helsinki metro calculated the rush hour car capacity requirement to be 36 cars. To make sure to meet that requirement in all conditions they ordered a total of 42 car pairs, which gives them a fairly good reserve.

A critical time as far as the car availability is concerned was in the beginning of revenue service, when the Helsinki metro ran a full-scale service with only 18 car pairs. At that time all cars were on the line during rush hours; no spare cars were then available.

Today the peak requirement for cars is during morning and afternoon rush hours; to carry all passengers requires altogether 30 car pairs simultaneously on the line. So, at the moment out of the 35 delivered car pairs 5 can be kept at the shop ready to replace a defective car pair.

The statistics of the maintenance shop give availability figures shown in Table 3.

Table 3. Car availability

Total car pair hours per year 6570 hours
Down times:
- preventive maintenance 160 hours
  - propulsion system 44 hours
- corrective maintenance 90 hours
  - propulsion system 45 hours
- other reasons 16 hours

Available car hours 6304 hours
Availability, total 0.96
  - propulsion availability 0.986

The down times include also the repair hours due to pattern failures, for example the replacement times of traction motors. Thus the availability figures due to the propulsion system will improve in the future.

7. Energy Consumption

A careful energy consumption analysis was done during the engineering phase of the rolling stock. According to the analysis, the overall consumption of the propulsion system was 4.8 kWh/car km (7.7 kWh/car mile). The energy flow of the analysis is shown in Fig. 10. The analysis did not include the auxiliaries of the cars.

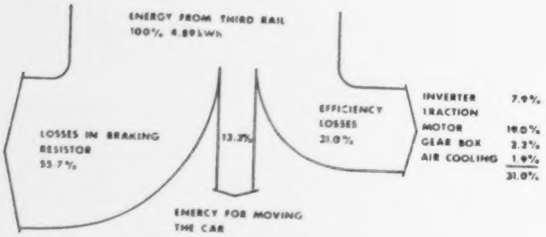

FIGURE 8 ENERGY BALANCE IN DRIVING WITH PROGRAM SHOWN IN FIGURE 7. WITH CAPACITY LOAD

Fig. 10. Energy flow of the ac propulsion system

Practical measurements give a total consumption of 2.5 kWh/car km (4.0 kWh/car mile), which also includes the consumption of auxiliaries. An estimated portion for propulsion system is about 1.8 kWh/car km (2.9 kWh/car mile). The big difference between calculated and measured consumptions is due to certain differences in conditions. The calculated energy consumption is with a crush loaded car, cruise-mode duty cycle and maximum speed. The measured consumption is a long-time average with often light cars, coasting duty cycle and most of the time reduced top speed.

As the system does not regenerate, all released braking energy is turned into heat by braking resistors. A part of the energy can be used to heat up the cars during the cold season. The rest is blown out. Because of the cold climate in Helsinki tunnel heating due to the braking energy is no problem. The tunnel is drilled into solid bedrock, which has a fairly constant temperature of 10 °C (50 °F) throughout the year.

8. Experience on technical characteristics

Performance:

The performance of the new cars has turned out to be very good. Both the initial acceleration and deceleration 1.2 m/s^2 (2.7 mphps) as well as the top speed of 80 km/h (50 mph) are sufficient to have a truly rapid transit system.

Riding comfort:

Most passengers say that they like to ride the metro, because it is fast and comfortable. Riding comfort is mainly due to the air suspension of the cars, but also the smooth and stepless acceleration and deceleration characteristics as well as efficient jerk limitation increase the riding comfort. The heating system using the braking resistor as one element also operates well. The temperature inside a car is stable even if the braking energy comes in "lumps". The passengers neither have to sweat in the stations nor to freeze between them.

Noise:

Because the Helsinki metro cars are mechanically well designed and consequently quiet, the traction motors and other propulsion equipment have to meet that feature and be quiet, too. Although at low speeds a typical "inverter tune" can be heard both inside the cars and on the station platforms, the noise is not in the least a nuisance.

EMI:

Comprehensive EMI tests and analyses have been done with the ac cars. As a review on the main conclusions is presented in another conference paper, only a brief summary is given here.

The Finnish Broadcasting Company has performed a series of tests to find out, if there is any radiated radio frequency (RF) interference. The tests have shown that broadcastings are not disturbed by the ac propulsion system. The disturbance level in telecommunication lines along the track due to audio frequency (AF) radiation has also been measured by the Helsinki Telephone Association with the same results.

As the Helsinki metro uses an AF train detection system, inductive EMI to the current loop formed by running rails and wheelset axles is also a potential problem. Measurements have shown that the induced voltage between the running rails is only few millivolts, which is not enough to make the track relay to malfunction.

Also conductive EMI has been analyzed carefully and lots of spectra of the line current have been recorded. Although there are certain harmonic currents, they have not caused any problems to the train detection or cab signalling systems.

Compatibility with automatic train control:

At the moment the Helsinki metro cars are driven manually, but provisions have been made also for automatic operation later on. Fort that purpose an ATC system was tested in the first car pairs during the experimental service. It operated reliably and controlled the train operation properly. The ATC system was not interfered by any of the EMI items described above.

9. Conclusion

The series M-100 metro cars in Helsinki have now been in revenue service for almost two years. The operating fleet is fairly big and still increasing, and the mileage covered by the fleet is high. As previous sections have shown, the reliability of the new ac propulsion system is excellent, car availability is high, maintenance is easy and brief, energy consumption is low and other technical characteristics are very good. The Helsinki cars are among the most modern ones in the world and they show today the good sides of the novelties. The difficulties caused by the new technology have mainly been overcome by today, and no big problems because of the ac propulsion system are experienced.

A similar experience is gained also from other transit properties where Strömberg has delivered ac propulsion systems. In Rotterdam, Holland, there are 33 ac light rail vehicles, which today run with a MDBF of some 80.000 km (50.000 miles). The LRV's have covered a toal distance of 1.3 million km (800.000 miles). In the City of Winterthur, Switzerland, 11 articulated trolleybusses have an ac propulsion system. They have run altogether some 800.000 km (500.000 miles) and run with a MDBF of approx. 180.000 km (110.000 miles).

As the experience gained both in Helsinki and elsewhere shows, ac propulsion is not only a technology of tomorrow. It runs today in many places at a very good reliability and with many technical and economical advantages.

Biography

Harri Holma obtained the M. Sc. (El. Eng.) degree in 1969 at Helsinki University of Technology. He has worked for Oy Strömberg Ab since 1972 as a design engineer and prototype office manager in the Electronics Division and a project engineer in the Traction Equipment Sales Group, where he has been responsible for several export projects. In 1982 he was appointed to his present position as the Urban Transit Office Manager of the Traction Department in the Strömberg Power Electronics Division of the Kymmene-Strömberg Corporation.

THE CHOPPER EVOLVES IN BALTIMORE

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Baltimore MTA
USA

Raymond T. Betler
Westinghouse Transportation Division
USA

This paper explores the decision-making process experienced by the Mass Transit Administration of Baltimore while procuring propulsion equipment for a new transit system. Means of controlling the design intergrity of that equipment is discussed followed by a description of the propulsion system and its operation. Maintainability and troubleshooting are examined along with details of the operational experience obtained during the prototype, testing, and startup phase of the program. The paper concludes with a brief analysis of future expectations in the transit industry.

INTRODUCTION

Six years ago, the Mass Transit Administration of Baltimore was confronted with the challange of procuring propulsion equipment for a mass transit system. The dilemna at hand was whether to go with a conventional cam controlled system or the relatively new chopper system. The cam controlled system had over 50 years of proven service, offered a single box design, would require mechanically oriented maintenance personnel, was smaller in size and weight and could be obtained at a lower initial cost. The advantages of the chopper system were defined in its: energy saving regeneration ability, capability of continuous motor control, easy adaptation with the vehicle's ATO and friction brake system, faster reaction time, and modular design for ease of maintenance. The obvious disadvantages of the cam controller system were no regeneration and discrete steps of motor control resulting in less smooth acceleration; and for the chopper system, increased cost and weight, the requirement for more sophisticated electronically/microprocessor oriented maintenance personnel, and a relatively limited duration of proven service (about 8 years at the time).

The requirement for sophisticated maintenance personnel was viewed to not be an insurmountable problem since several of the other vehicle systems such as ATO, air conditioning, and doors utilized microprocessor technology. Also, most maintenance personnel would be hired in new and would not require retraining to adapt their capabilities from cam controlled-mechanically oriented to chopper controlled-electronically oriented troubleshooting. Another consideration was the possibility of future expansion. The microprocessor would provide the distinct advantages of expandability and flexibility. Circuit parameters could be easily altered via software as opposed to hardware. Maintainability of an entirefleet could be greatly enhanced by the capabilities of the microprocessor based logic. Utilization of a microprocessor was viewed to result in substantially reduced life cycle costs. In addition, the everchanging state-of-the-art in propulsion and electronic technology seemed to be sound reasons warranting startup with a chopper system.

After the relative merits and shortcomings of each system were defined, a thorough evaluation process was performed by the MTA, its joint procurement partner Metro Dade County, Florida and their consultants. Chopper propulsion was chosen as the result of this decision-making process leading to the state-of-the-art chopper system which exists in Baltimore today.

As of October, 1983, a total of 58 vehicles were delivered from the Budd Company. A total of 72 vehicles are scheduled for delivery under MTA's initial procurement along with 28 additional vehicles purchased through an option order. While the system is currently in its start up phase, the vehicle fleet has accumulated a total of 100,000 miles over a 15-month period. Revenue service began November 21, 1983 operating six-car trains.

A total of 136 nearly identical cars are being delivered to Dade County, Florida.

DESIGN CONTROL

The specification to procure propulsion equipment was a joint venture for the transit administrations of Baltimore and Miami, developed utilizing consulting support. The commonality of requirements from this dual purchase has resulted in product standardization and a minimization of development duplication.

Equipment design was coordinated and controlled not only by the procurement specification but also through the implementation of design reviews, failure modes and effects analyses, reliability analyses, first article inspections/approvals, and maintainability analyses. The design was verified through systems, environmental, shock and vibration, EMI and maintainability testing. In addition an extensive vehicle test program was performed at the Pueblo test facilities.

EQUIPMENT DESCRIPTION/FUNCTION

The Westinghouse chopper system selected for use in Baltimore consists of a semiconductor box, motor control box, line switch box, line reactor, motor reactor, knife switch box, brake resistor assembly, propulsion blower, propulsion logic assembly, traction motors, gear units, power/brake signal generator, master controller and converter (See Figure 1).

Semiconductor Box

The semiconductor box controls the average current through the traction motors in power and brake while limiting the amount of ripple on the line. The equipment housed in the semiconductor box includes the power thyristors and diodes, commutating capacitors and inductors, gate pulse amplifier assembly, line filter capacitors, ground fault detection transducer, voltage divider panel and fuse counter panel.

The power semiconductors are mounted in double sided aluminum finned heatsinks. All power connections to the heatsinks are made by means of copper busbars which minimize weight and space requirements along with downtime needed for heatsink replacement. Snubbers are mounted directly on the heatsinks which reduces the inductance between the device and the snubber and eliminates the possibility of mismatching devices and their specific snubber circuit.

The commutation capacitors and inductors are used to store the energy and establish the ringing circuit needed to turn the thyristors off.

The filter capacitor assembly is made up of fifteen capacitor modules, each housing four individual cans. In the event of a failed capacitor, the module in which it is housed can be replaced in a very short period.

The gate pulse amplifier electronic assembly converts firing pulses transmitted by the logic to the thyristor gates through an isolation transformer housed on the heat sink assembly.

A ground detection transducer in the semiconductor box monitors return line current and provides a feedback signal for interpretation by the logic.

The output of the voltage divider panels provide feedback signals used to monitor and control the system corresponding to; filter capacitor voltage, commutating capacitor voltage, brake resistor voltage and the number of opened filter capacitor parallel paths in the filter bank. The semiconductor box is forced air ventilated.

Motor Control Box

The motor control box contains the electro-mechanical devices (reverser, power controllers, and contactors), in addition to the relay logic and sensing components required to properly distribute propulsion power.

The reverser is a rotary drum electro-pneumatic device used to change the direction of current flow through the motor fields resulting in a direction reversal.

The controller assemblies housed in the motor control box include the field controller, loop controller and power-brake controller. Each controller is an electro-pneumatic device which is actuated by energizing a magnet valve. The field controller is utilized for changing from a full motor configuration to a field parallel (50% motor field) configuration. The loop controller is used to make up the brake circuit by connecting the four traction motors in a two series, two parallel configuration. In addition, it opens the motor loop during removal of power. This prevents the possibility of self-excitation during towing which could result in damage to the motors. The power-brake controller connects the motors to the chopper and line. In power, the chopper is connected to the high side of the motors. In brake, the high side of the motors is connected through a dropping resistor bank to the line.

"UNDERFLOOR PROPULSION EQUIPMENT - LOOKING THROUGH FLOOR"

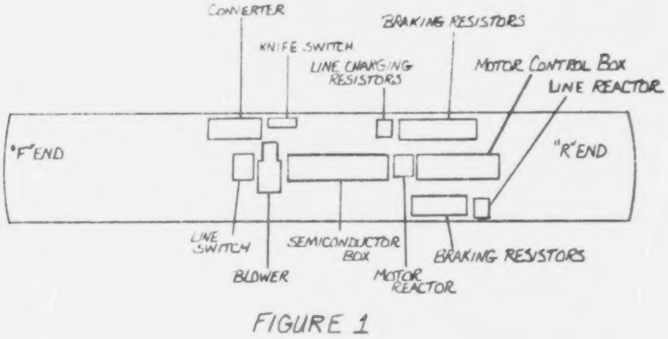

FIGURE 1

Four single pole magnetic contactors are used to control the amount of resistance in series with the motor during brake. Switching of these contactors is controlled by the logic based on motor speed. A brake overload/build down contactor is used to short the motor field forcing the generated motor current to zero in the event of an overload/fault while in the brake mode.

The remainder of the motor control box is occupied by a control relay panel. Mounted on the relay panel are the overload relays used to sense excessive motor current in power and brake, three transducers for sensing current in each motor path along with incoming line current, a build up contactor which provides a brake build-up assurance circuit, and a power brake relay which is a vital relay interlocked with the power brake controller.

Motor Reactor

Current ripple to the motor is limited by an iron core motor reactor. By limiting this ripple, motor current losses are reduced and commutation is improved.

Line Reactor

This iron core reactor in conjunction with the filter capacitor assembly limits the ripple induced on the line by the chopper.

Braking Resistors

The braking resistor bank consists of groups of ribbon wound resistor tubes used to regulate current and dissipate, in heat, the power generated by the traction motors in braking. The total resistor bank is sized based on the assumption that the line will be totally non-receptive.

Knife Switch

The knife switch is a single pole double throw switch with a quick break copper blade and three sets of copper jaws. The knife switch can either be in the fully closed running position, in the partially closed auxiliary only position or in the fully open position which permits access to a test bug for shop use.

Line Switch Box

The line switch box houses two electro-pneumatic contactors, a main fuse, a line charging resistor fuse and a blower motor resistor and fuse. Two line switches are used to reduce voltage stress and to control line charging and fault current limits.

Propulsion Blower

The propulsion blower is used to force cool the semiconductor box, motor control box and motor reactor. It is driven by a 2 horsepower d.c. motor designed to output at least 1700 cfm of air at a 3.5" pressure drop.

Converter

The low voltage systems on the car are powered by an auxiliary converter. The converter is used to maintain charge on the batteries and to regulate low voltage power. The converter takes D.C. line voltage, converts it to an A.C. voltage via SCRs, which is rescaled through a transformer and outputs isolated low voltage D.C. by means of a bridge rectifier.

Logic Assembly

The propulsion logic assembly, housed in the cab area, is used to continuously monitor and control the performance of the chopper equipment. The logic assembly consists of five PC boards; a digital input board which receives feedback signals and transmits them to the microprocessor; a digital output board which outputs control logic signals to the electro-mechanical contactors and controllers: an analog output board which provides the firing signals to the thyristors; an analog input board which receives feedback signals from the voltage dividers, tachometer, transducers and the P-signal request; and a CPU board which houses an 8080 microprocessor and its associated support chips, RAM, and the PROM which is programmed to characterize the propulsion system.

Power/Brake Signal Generator

The power/brake signal generator is an electronic assembly consisting of three P.C. boards and four transformers. It reponds to the master controller request by sending a mode signal to the logic along with a current magnitude corresponding to tractive effort request.

Master Controller

The master controller consists of an on/off switch, a mode selection switch, and a main controller handle. The main handle controls the level of request through a rotary potentiometer.

Traction Motors

The car is propelled by four Westinghouse 1462-D traction motors. These self-ventilated motors are designed to operate to a top speed of 70 mhp. They will produce a 3.0 mphps rate in both power and brake.

Gear Units

Westinghouse WR-501 gear units transmit the mechanical torque of the traction motor to the axle of the vehicle. The gear unit ratio is 5.723 to 1.

MAINTAINABILITY/TROUBLESHOOTING

A strong effort was made during the design phase to develop easily maintained equipment. The heatsink assemblies in the semiconductor box are mechanically keyed to prevent erroneous replacement. The filter elements for the propulsion blower are integrally housed and readily accessible for easy replacement. If the logic senses an open filter capacitor path, performance is reduced slightly; however, vehicle availability is not affected until four paths are electrically opened and the system is shutdown. Modular packaging techniques are incorporated throughout the equipment.

Aside from the enhancement of maintainability due to modular design, several pieces of test equipment are available to compliment normal troubleshooting. The logic assembly has a blank slot for inserting a monitor P.C. board. The monitor board can be used for troubleshooting the logic and the propulsion system. The output from the monitor board can be displayed on a chart recorder or on six sets of hexidecimal leads housed on the board. Any propulsion logic signal or microprocessor memory location can be observed via this monitor board. Thus, it can be an invaluable tool for maintenance personnel.

A propulsion simulator will be used to test the logic assembly. By connecting the logic assembly to the simulator, the functional operation of the logic can be verified. The simulator is a modification of a logic assembly which is programmed to mimic the remaining propulsion equipment. It can be used as a bench tester if a logic problem is suspected or if it is desired to check out a logic before its installation on a car.

A portable converter tester will be used to verify the functional operation of a converter. The 20 lb. portable tester is connected to the converter using a control plug on the side of the box. The tester functionally sequences the converter and determines its status without ever opening the box covers.

Similarly, a portable tester exists for the motor control box. It is also connected externally to the side of the box and functionally exercises the components within the box. While it can operate the controllers and contactors in the motor box, not all interlocks on each device are checked nor can proper controller sequencing be determined.

A more useful troubleshooting tool being considered is a test prom programmed with a test routine and housed on the CPU board in every logic assembly. The test prom would be activated by placing the logic in the test mode. The test routine could be programmed to sequence all devices and functions required to simulate normal operation. The specific interlocks and feedback signals associated with those devices/functions used during normal operation would be checked during the test routine. A major advantage of this type of testing is that the test prom only requires a software program and the addition of one chip. All other interfaces required are already in place from normal logic operation.

RELIABILITY

Reliability analysis were performed for each item of propulsion equipment. Many design efforts were taken to enhance component and system reliability. All semiconductor devices are rated for a minimum of twice line voltage. Filter capacitors have been designed to zener below the device voltage rating. In addition, the semiconductors are designed to operate at a junction temperature of 80°C versus a rated junction temperature of 125°C. Snubber circuits have been designed to limit dI/dt (during turn-on) and dV/dt (during turn-off) stressing considerably below the device capability. Filter capacitors are applied at 65% rated voltage.

The propulsion system mean time between failure for a two car married pair is calculated to be at least 1200 hours.

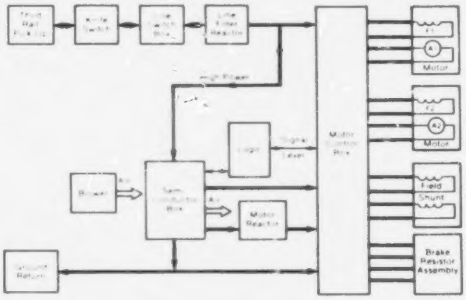

FIGURE 2: EQUIPMENT INTERFACE

OPERATION

The functional interface of the propulsion equipment can be seen in Figure 2. A detailed power schematic of the system is shown on Figure 3.

When the logic receives a propulsion request, the line switch and power brake controller are closed. This allows the filter capacitors to charge to line voltage. The logic then fires T2 allowing he commutating capacitor in the main chopper to charge to line voltage. The magnitude of the request signal from the master controller is sensed and T1 is fired. During startup, on-pulse skipping of T1 occurs to control the rapid buildup of armature current. Current is ramped up from 0 to 775 amps (max P signal) per motor in 1.5 seconds. Acceleration is jerk limited at a rate of 2 mphpsps. In order to turn off the main chopper, a T2 pulse is fired. Firing of T2 allows the commutating capacitor to discharge and reverse bias T1. The T1 thyristor is fired at a rate of 283 hertz. The subsequent firing of T2 during this 3533 microsecond cycle is dependent on current request. When the current reaches the motor curve, T2 pulses are suppressed allowing the chopper to remain full on and full line voltage to be impressed on the motors. Field shunting occurs at 30 mph.

When a brake request is received by the logic the power brake controller is transferred from the power to brake position and the loop controller is closed. The chopper is now connected to the low side of the motors and is utilized to maintain the regulated braking current required to achieve a 3 mphps deceleration rate. Operation of the main chopper is the same in brake as in power. A secondary braking chopper is now available for use, in the case of a nonreceptive line. Turning the T5 chopper on inserts R5 resistors in series with the R1 R2, R3 and R4 dropping resistors.

Sensing fault conditions during operation is done electronically by the logic and/or electromechanically by the overload relays. Should a fault condition occur, three means of sensing and limiting the fault exist. The chopper is phased back to limit the fault current. At the same time, the line switch will be opened. The reaction time of the line switch is about 70 msec. If the line switch is unsuccessful in clearing the fault, it is backed up by a line fuse.

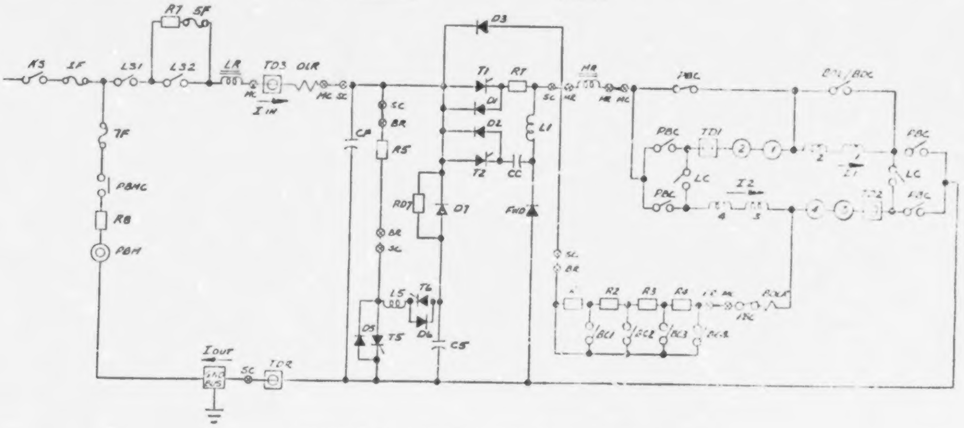

FIGURE 3 - SIMPLIFIED POWER SCHEMATIC

TESTING/OPERATIONAL EXPERIENCE

Since revenue operation in Baltimore is just beginning, most of the knowledge/experience obtained to date has been gained through prototype, system, maintainability, Pueblo, and startup testing and operation.

Testing was performed during the prototype stage to determine the best electrical configuration of the filter capacitor assembly to minimize line ripple and maximize the effectiveness of the total bank capacitance. It was determined that each path of four series capacitors (fifteen paths total) should be wired directly to the incoming positive and negative line voltage cables. This reduces the inductive losses present in a single lumped capacitor bank.

Motor current ripple measured during testing was about 12%. Line current ripple induced from the chopper was also measured and found to be below 5%.

Brake resistor switching points were altered during system testing to determine the maximum speed at which a step of dropping resistors could be switched out without losing control of the traction motors. Measurements proved that approximately 50% of the total available braking energy can be regenerated to a fully receptive line.

EMI testing to the chopper prototype box determined that shielding of the box and/or commutating reactors made no difference in induced interference. A significant difference was noted, however, by the rearrangement of commutating components and their interconnecting cable. As a result, the commutating components are configured in as close a physical arrangement as possible such as that their flux oppose.

A very useful finding was noted during EMI testing of the propulsion system. It was found that simply by reorienting the motor reactor 90^o from its original position, the induced noise from the propulsion system could be reduced dramatically. This resulted in a difficult and rather unsightly rerouting of the propulsion blower duct but drastically reduced any possibility for interference between the propulsion and signalling systems.

Subsystem	Mean Time To Repair Spec.	 Actual	Max. Corr. Main. Time Spec.	 Actual
Power & Traction	2.20	0.83*	4.86	1.40**
Misc. Electrical	1.50	0.59*	3.32	0.77**
Train Control	2.00	0.88*	3.58	1.53**
Friction Brake	1.00	0.58*	2.21	0.59**

(All figures in hours)

* Upper 80% confidence limit
** 90th percentile Mmax.

TABLE 1: MAINTAINABILITY TEST RESULTS

Extensive EMI testing was also performed on the vehicle by Westinghouse to determine the compatability of the chopper with the ATP equipment. Test conclusions were that no locations of incompatability exist when conductive interference generated by the chopper is compared with the sensitivity levels of the Union Switch and Signal/ATP equipment.

A maintainability test was performed to demonstrate compliance to the mean-time-to-repair and maximum corrective maintenace time specification requirements. Test results verified the benefits of the effort made to design ease-of-maintainence into the equipment. (See Table 1)

Minor startup problems were experienced requiring corrective action. An abnormal failure rate of free wheeling diodes resulted in the development of a snubber circuit to provide additional device protection. The devices were found to be suffering dV/dt failures resulting from T2 being fired while the free wheeling diode was conducting. The free wheeling diode failure rate has essentially gone to zero since the incorporation of the snubber circuit.

Faulting converters and failed SCRs resulted in relocating the thyristors gate transformers and rerouting the gate lead wires. The wires previously were routed together on the bottom of the box, from the gate transformers on the logic board to the thyristor assembly. It was found that when one thyristor was fired sufficient noise was generated in its gate leads to induce a firing pulse in the opposite thyristor. The resolution to the problem was found in removing the gate transformers from the logic board and mounting them on the thyristor assembly. This effectively reduced the gate lead length from 3 feet to 3 inches. At the same time, the wires running from the logic board to the thyristor assembly were separated from one another and from the box itself with a set of spacers. Under the same operating coniditions, the induced noise after the modification was reduced by a factor of 20 to 1 compared to the original design.

Problems were encountered with the field controllers. The controllers would arc when going from 100% to 50% field. This would cause the cam switch contacts to weld closed preventing the controller from reconfiguring to 100% field. The effective result was shorted fields when attempts were made to reconfigure, driving the motor current to zero. The solution to the problem was the substitution of a new magnet valve assembly with larger ports. This resulted in a faster controller, very little arcing, and no sticking.

Also, several software changes were made to the logic to fine tune the system/chopper performance during system testing and startup.

FUTURE EXPECTATIONS

We are convinced that the Baltimore vehicles are equipped with the most sophisticated in available propulsion system technology. We recognize, however, that changes are inevitable and in most cases desireable. Propulsion systems of the future will undoubtly be drastically impacted by the ever changing semiconductor, electronic and microprocessor technologies. Indeed, the analog designer is becoming extinct. Westinghouse has already made the design change from an 8-bit to a 16-bit microprocessor. The transition from standard thyristors to gate turnoff devices is being explored. This will allow the elimination of commutating circuits and will result in lighter, smaller and more cost effective equipment. The elimination of all electro-mechanical and electro-pneumatic devices from the propulsion system is presently being explored. New components and subassemblies are continually created as a result of higher performance and decreased size/weight requirements. Value engineering efforts are pursued to increase cost effectiveness while improving reliability. New packaging and cooling techniques are being explored and developed with the intention of eliminating internal forced air. These techniques would also increase the cooling capability of the equipment requiring less mass and space. The complete interface, design and supply of friction brake, propulsion and ATO equipment is currently being pursued by Westinghouse. To allow the full benefit of these technological improvements, both transit car operators and propulsion suppliers must remain flexible and adaptable.

OPERATIONAL EXPERIENCES WITH MICROPROCESSOR-BASED TRAIN CONTROL

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Abstract

This paper is based on three and one-half years of experience in the operation and maintenance of a microprocessor-based control system as used in the ATLANTA HARTSFIELD INTERNATIONAL AIRPORT AGT system. Included is a brief system overview and a discussion of advantages gained in microprocessor control as related to reliability, long-term operational stability, and spares inventory. System maintenance and fault diagnosis techniques are also discussed.

Introduction

Prior to microprocessor technology, the control systems used in People Mover applications were discrete component analog systems. These systems required careful and frequent adjustment and, as components aged, the system response would change. With the introduction of microprocessors, the Westinghouse Transportation Division control systems for transit vehicles were re-designed to incorporate the many advantages of this new technology. The first full application of this design was realized in the ATLANTA HARTSFIELD INTERNATIONAL AIRPORT AGT system.

The basic design concepts of the ATO system used in Atlanta were originated by Westinghouse Transportation Division in 1976. In addition to the ATLANTA AIRPORT application, the same basic ATO design is in use with AGT systems at ORLANDO INTERNATIONAL AIRPORT, GATWICK AIRPORT in the United Kingdom, and with the soon to be operational METROMOVER system in downtown Miami. Another version of this microprocessor-based ATO system is in use in the SAO PAULO TRO system in Brazil. The primary erences between the applications are the packaging and the interface with the vehicle propulsion system.

System Overview

The ATLANTA AIRPORT AUTOMATED GUIDEWAY TRANSIT (AGT) system has been in operation since September 28, 1980. This system provides transportation to approximately 75,000 people per day, carrying passengers between the main terminal area of the Atlanta International Airport and four concourses. The system consists of twelve stations, 12,000 feet of guideway including thirteen guideway switches, and a fleet of 24 vehicles. The vehicles may be operated individually or coupled to form 2-car or 3-car trains. The normal system operation consists of six 2-car trains. During peak periods of heavier than average passenger flow, some of the 2-car trains are replaced with 3-car trains to handle the additional passenger load. The trains operate at a maximum speed of 25 mph with headways of approximately two (2) minutes. This system operates 20 hours per day, 7 days per week, and requires no on-board train operator.

Atlanta Vehicles

The Atlanta vehicles are 39 feet long, 9 feet 4 inches wide, 11 feet high and have an empty weight of 30,000 pounds. Each vehicle has a capacity of 80 passengers. The vehicle is equipped with rubber tires and runs on a concrete guideway; it uses a steel "I" beam for guidance, and is locked to the guidebeam by eight solid rubber guide tires. Each car has two collector assemblies containing contacts to pick up 600 volt, three phase AC power, and contacts to provide for track circuit occupancy and speed code detection. Propulsion is provided by two 100 horse-power DC motors per vehicle. Three braking modes are used in the system: dynamic, air, and spring emergency brakes. Propulsion and dynamic braking is controlled by varying the firing angle of thyristor rectifiers fed by the three phase power. Figure 1 shows a typical transit vehicle.

Each vehicle contains a complete Automatic Train Operation (ATO) system. This system contains two computers with associated input/output modules, receivers for speed code data, door and graphics data, and program stop information. The remainder of the ATO system consists of modules to interface with the braking and propulsion, vital overspeed, door, graphics display, and voice message announcement systems.

Another method which has proven to be most helpful consisted of a remote terminal and EPROM programmer at the field site, connected by modem to a similar unit at the headquarters office. The field service engineer contacted design engineering concerning a possible software defect, describing the occurrence in detail. The design engineer reviewed the software list, made a minor revision, and transmitted the new program to the field site via the modem. A new EPROM was blown, installed in the vehicle, and verified under actual operating conditions in less than one hour.

Long-Term Operational Stability

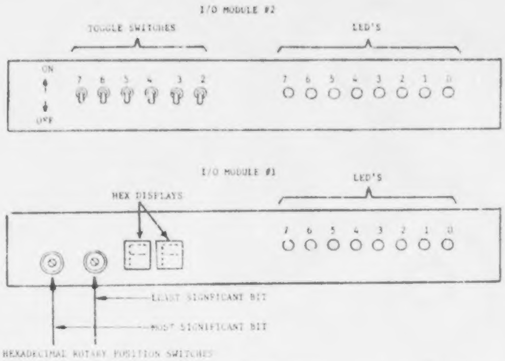
Prior to microprocessor-based train control systems, careful tuning and adjustment of a sub-system was required. During system operation, as discrete components aged and characteristics changed, re-adjustment was required. This is not necessary with a microprocessor-based system. For example, the speed maintaining program in the ATO software simulates a proportional integral differential controller. The gain constants are set with software. As the system ages, these gain factors do not vary, giving much improved long-term stability as compared to an analog system.

Ease of Diagnosis

The flexibility of the microprocessor-based train control system has made it possible to incorporate many diagnostic routines into the software, helping to make fault analysis and isolation much faster for the maintenance technician. In addition, the need for external test equipment is minimized.

When a fault with the train control system occurs, all conditions relevent to train control operation at the time of the fault are stored in the computer. As many as fifteen (15) input/output conditions are stored and remain in the computer until the information is retrieved by the maintenance technician and the stored data is cleared. The stored data is displayed on a simple "GO/NO-GO" LED front panel display. The first step in troubleshooting the fault is to observe the display and use the missing LED indication as a starting point for tracing the problem. Figure 2 shows a diagnostic indication display panel.

Maintenance of the microprocessor-based train control system is simplified with the easy replacement of individual printed circuit modules which are considered Line Replaceable Units (LRU). Repair of the LRU in many cases involves the replacement of the suspect module with a known good module. The faulty LRU is then return to WTD for repair, thus reducing the general technical skills required by the maintenance technician. An equipment cradle with associated modules is shown in Figure 3.



KEY

U – Up
D – Down
- – Indeterminate
* – One switch must be down
0 – Switch down to display only hex to address displayed. Switch up to latch displayed address allowing selection of a second non-display address, the data of which will appear on the respective I/O #1 module.

Monitored Parameter	Switch					
	7	6	5	4	3	2
MEMORY PAGE 0EH	D	0	D	-	D	D
MEMORY PAGE 0FH	U	D	U	-	D	D
LATCHED ADDRESS	U	0	D	-	D	D
ALARMS DISPLAY (CPU-2 ONLY)	D	-	-	D	D	D
DIAGNOSTICS DISPLAY	D	-	-	D	U	D
LAMP TEST	-	-	-	-	D	U
FAILURE TEST	-	-	*	*	U	*
(SET) ALARM TEST (CPU-2 ONLY)	D	U	U	U	U	U
(SECOND) ALARM TEST (CPU-2 ONLY)	U	D	U	U	U	[illegible]
(THIRD) ALARM TEST (CPU-2 ONLY)	D	D	U	U	[illegible]	[illegible]

Figure 2 - Diagnostic Indication Panel

Figure 3 - Equipment Cradle With Modules

Our operational experience in Atlanta has revealed three factors which will be improved upon in future microprocessor-based systems:

- what information to alarm
- how to make the alarms more reliable
- how to fully utilize the potential capabilities of the computer

BEST COPY AVAILABLE

Which events to alarm, as well as the reliability of the alarm system, will reduce the number of false alarms which tend to cause the important ones to be missed. Learning how to better utilize the capabilities of the computer will assist in the storage of relevant data required for troubleshooting. Access to this information is most important when attempting to resolve intermittent problems.

Spares Inventory

The microprocessor-based train control system, as designed by Westinghouse, allows for a reduced spare parts inventory. The design makes both computers identical except for the software programs, thus reducing the number of unique modules required for adequate spares support of the system. Coupled with the increased reliability features, this can result in an overall reduced cost of ownership for the ACT system.

New Personnel and Equipment Requirements

To fully utilize the tremendous flexibility and operational advantages of the microprocessor-based train control system, some new and different personnel skills as well as support equipment are required.

Much of the microprocessing technology is new and many of today's technicians and technical school graduates do not have all of the basic skills necessary to troubleshoot and fault isolate the microprocessor-based equipment. At Atlanta, we found it necessary to provide additional training in basic programming skills and a greater understanding of microprocessor technology to our maintenance personnel so that they were able to maintain the system effectively. While programming skills are not required of the maintenance technician, a basic knowledge of the programming structure is invaluable for an understanding of the overall operation of the system.

When incorporating modifications and improvements at a field location, it is necessary to provide the site with adequate equipment to easily re-program multiple EPROM units rapidly. By experience we have found the 121A Gang EPROM Programmer, manufactured by DATA I/O, is adequate to meet our needs. This unit will simultaneously program 20 identical devices or up to five sets of four EPROMs.

Summary

Westinghouse Transportation Division has more than three and one-half years of operating experience with the microprocessor-based train control system in use at the ATLANTA HARTSFIELD INTERNATIONAL AIRPORT. The experience gained has proven that the system:

- o provides increased reliability
- o has long-term operational stability
- o provides flexibility for improvements or modifications
- o has simplified diagnostics and maintenance procedures
- o can provide lower cost of ownership
- o requires new personnel skills and support equipment

Biographies

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Mr. Hadden received his BSEE degree in Electrical Engineering from the University of Michigan in 1951. He is a Senior Member of IEEE, and a Member of the Society of Logistics Engineers (SOLE). Mr. Hadden has 33 years of experience in field engineering and general management functions with Westinghouse Electric Corporation. He is presently Manager, Field Operations for Westinghouse Transportation Division with responsibility for all field activities related to People Mover and mass transit products.

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Mr. Kenyon received an AA degree in Electronic Communications from American River College in 1962. He is a Senior Member of IEEE, a Senior Member of ISA, a Member of ASOC, and a Member of the Society of Logistics Engineers (SOLE). His present function is Manager of Field Engineering, Headquarters Operation. In this capacity, he has management responsibility of field engineering, technical support, logistics engineering and field reliability data acquisition for the division. Mr. Kenyon has over 25 years of experience in field installation, testing and engineering.

UTILIZATION OF MICROCOMPUTER ON THE NEW TRANSPORTATION SYSTEM

Yutaka Maeda
Chiyoharu Tonda
Takayoshi Nakatani
Osaka Municipal Transportation Bureau
Japan

Summary - The new transportation system in Osaka City, named NEW TRAM, consists of total system based on is the advanced and safe automatic operation system using the latest technology on railways. This total system is made up by two minicomputers for traffic control and about 110 microcomputers for on-board ATO equipment and other facilities to perform very extensive and efficient control.

Especially, there are two major utilizations of microcomputers. One of them is Multiplex Communication Control on "Data Transmission System with Trans" that transmits and receives various informations between the central control and trains. The other one is Interval Control of Trains on Moving Block System that keeps safety between multiple running trains in one block meaning of traditional fixed block.

Consequently it can be said that the utilization of microcomputers is considerably effective for the total system configurations.

Introduction

The South Port area, a reclaimed land, is located in the southwest of Osaka and covers an area of 930 ha. This new land utilization plan was implemented so as to provide harbor facilities and a residential district of the most advanced design with harmony and comfort as the goals.

The Port Town located on the center is a town covering 110 ha, having the population of 40,000 and installed with many modern urban facilities.

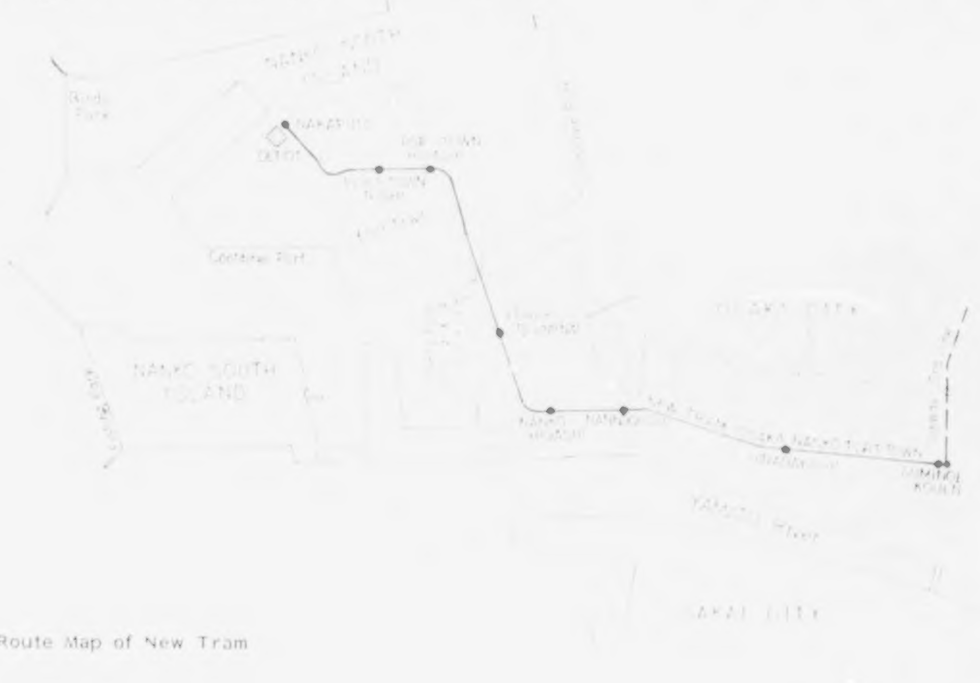


Fig.1: Route Map of New Tram

As an access transportation from city center to this area, an intermediate capacity transit system named New Tram was inaugurated on March 16, 1981. New Tram, employing the steering wayside guide system is a fully automated guideway transit system and runs on 6.6 km of elevated double concrete tracks with rubber tired vehicles. There are 8 stations from Suminoekoen Subway Station to Nakafuto Terminal of Port Town, the traveling time is about 14 minutes by 50 km/h maximum speed.

A train consists of 4 cars which is similar to bus size and the capacity is about 300 passengers.

The power supply to vehicle is three phase AC 600 V. The train operation including starting and stopping, door operation, public address system on each train etc. are controled automatically by on-board ATO equipment and Station Control Unit at each station.

The observation for scheduled operation, routing, information service system and public address system on total trains and stations are controled by the central computers. As signal and communication equipment, there are ATC/TD (Automatic Train Control/Train Detector), train wireless telephore, emergency stop, station supervising TV system by optical fibre cable and so on.

The above mentioned sub-systems using computers and microcomputers are composed to total system to permit unmanned train operation and labor saving. (Fig.1)

Utilization of Microcomputer

The New Tram uses two minicomputers for operation arrangement and about 110 microcomputers for vehicles, signaling, communication and station service devices. These microcomputers work as a subsystem with combination or independence.

Devices involving microcomputers are as follows.

(1) Data transmission between wayside and train
(2) Train wireless telephone
(3) Moving Block system
(4) Data transmission between central control and each station
(5) On-board ATO
(6) Public address system on platform

Among them, the data transmission and moving block system are described below.

Data transmission system

Outline of the system

This system, consisted of central control station, fixed station and on board station, is provided for data transmission between control center and each train.

The status data of the train is transmitted to the central control center and displayed on the console desk and the display panel. At the same time, these data is transmitted to the central computer. Conversely, commands from the computer or the console desk are transmissted to trains. This system adopts the method of time sharing multiplex communication with full duplex polling selecting control. Transmission speed is 1200 bit/sec. and transmission interval of central control station and each on board station is every one second.

Composition of hardwares

(1) Central control station

Located at the control center and composed of Multiple Communication Control Unit (MCCU), Modulation-Demodulation Unit(MODEM) and recording devices.

Central control station is consisted of duplex system and can be switched automatically or manually. MCCU and MODEM have 8 channels CCU and MODEM for each communication section which divides the guideway line into 8 areas. MCCU and CCU are made up by microcomputer.

(2) Fixed station

Composed of carrier transmitters placed at the three stations and twisted parallel line type inductive radio transmission line on the track surface.

(3) On-board station

Composed of data transmission device and antenna on board. Each train has two sets. (Fig.2)

Function

(1) Communication method

According as train runs, communication section is shifted. Therefore MCCU keep up with the train which transfers sections to continue the communication with it. MCCU controls the communication to trains by full duplex polling selecting call through every channel, and each train can receive the communicative service from MCCU by every one second. One second is divided into seven time-slots at each communication section. MCCU communicates with the train in that communication section within one time-slot. Namely, data transmission to train takes multiple time and space division system. (Fig.3)

Fig.2 Composition of Data Transmission System

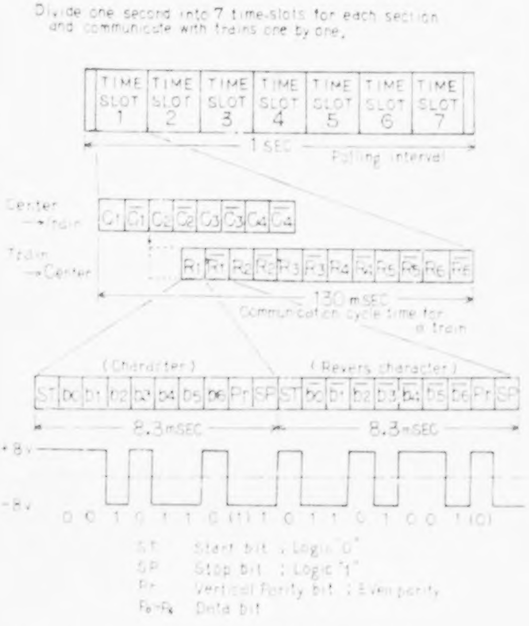

Divide one second into 7 time-slots for each section and communicate with trains one by one,
TIME SLOT 1
TIME SLOT 2
TIME SLOT 3
TIME SLOT 4
TIME SLOT 5
TIME SLOT 6
TIME SLOT 7
1 SEC
Polling interval
Center → Train
Train → Center
C_1 $\overline{C_1}$ C_2 $\overline{C_2}$ C_3 $\overline{C_3}$ C_4 $\overline{C_4}$
R_1 $\overline{R_1}$ R_2 $\overline{R_2}$ R_3 $\overline{R_3}$ R_4 $\overline{R_4}$ R_5 $\overline{R_5}$ R_6 $\overline{R_6}$
130 mSEC
Communication cycle time for a train
(Character)
(Revers character)
ST b0 b1 b2 b3 b4 b5 b6 Pr SP ST $\overline{b_0}$ $\overline{b_1}$ $\overline{b_2}$ $\overline{b_3}$ $\overline{b_4}$ $\overline{b_5}$ $\overline{b_6}$ Pr SP
8.3mSEC
8.3mSEC
+8v
-8v
0 0 1 0 1 1 0 (1) 1 0 1 1 0 1 0 0 1 (0)
ST Start bit ; Logic "0"
SP Stop bit ; Logic "1"
Pr Vertical Parity bit ; Even parity
b_0-b_6 Data bit

Fig.3 Data Transmission System

The sensible errors during data transmission to train and response data reception from train are as follows:

(a) Time out check
(b) Vertical parity check
(c) Synchronous check

(2) Central Control station/Fixed station transmission-on board station reception.

When the data for train control and commands are transmitted from the control center to each train, MCCU selects the train and coverts the parallel code into series code, then this code is modulated with PM modulation and transmitted to train through inductive radio cable. Transmission unit on-board demodulates this code and converts into parallel code and sends the data to ATO (Automatic Train Operation), audio announcement equipment.

(3) On-board station transmission-fixed station/central control station reception.

When the data are transmitted from each train to control center, on-board transmitter converts input data of each on-board unit into series code, then makes FS-PM modulation and transmits them.

On the ground, the modulated data which are received through inductive cable are demodulated by carrier unit and sent to MODEM unit. MODEM unit demodulates this FS wave into series code and send to MCCU. MCCU makes series-parallel code conversion and sends the data to central computer, operator's console and so on.

(4) Communication data

The data from train to control center consist of "Train abnormal information" and "Train Status information", and the data from control center to train consist of the intervention or modification commands on an accident and service jobs. The data from control center to train are composed of 4 characters (1 character --- 7 bits + parity bit) and 6 characters vice versa.

Moving block system

Outline of the system

Usual fixed block system adopted on the present railway is not so enough to comply with the request for shortening of train interval because of the limitation of the number of blocks.

From a long time ago, various kinds of moving block system were invented and we also introduced the experimental moving block system at the depot area.

According to the detection of the absolute location address of the train, ATC signal is controled by triplex microcomputers to keep the minimum space between trains or to restrict over speed.

So, this system is composed of the data transmission, location detection and ATC control devices. The location of train is detected with the accuracy of one meter on the loop line around the depot. Thus maximum four trains can exist in one fixed block which includes 451 locations.

Train depot and Maintenance yard operation

The train depot is equipped with various facilities for car inspection, overhauling, repairing, cleaning and parking. The New Tram's depot must have the following functions in addition.

(a) Departure test line
 To test the automatic control ability of ATO equipment on board.
(b) Trial run of train
 The test of un-manned train operation can be performed passing through the loop around line of depot area.

The test schedule and route are controled automatically by minicomputer to save labor.

Composition of hardwares

(1) Data transmission device

This device is consisted of MCCU and MODEM and carrier unit. The depot area is divided into 3 sections, so MCCU has 3 communication channels and controls time sharing multiplex data communication to trains through these 3 channels.

Original purpose of this device is data transmission to trains. On this system the signal from train to wayside is used for location detection.

(2) Location detection device

Composed of data receiver and inductive radio cable with multi twisted pairs of lines laying on the track around the depot. Receiver is triplex system and the absolute location of train is detected on gray code with the accuracy of one meter. This system doesn't demand the special on-board devices for location detection, because of using on board station device of data transmission system.

(3) ATC control device for the loop track around the depot

According to the contents of the data and train's absolute location, this device controls the ATC device directly. Processing is performed with software of microcomputer. To realize the high reliability, the system is triplex and output is decided by majority. (Fig.4)

Function

(1) Detection of train location

The location detection device receives the carrier from on board data transmission equipment through the twisted pairs of inductive radio lines, and detects the location of train with the accuracy of one meter.

The principle of detection is shown in Fig.5.

The widely spaced section pairs of lines represents "1" in binary digit and the closely twisted section pairs of lines represents "0", so if there are n pair of lines which gives the absolute address pattern pairs, maximum 2^n locations can be represented.

The example of real arrangement of pairs of lines is shown Fig.6.

In this example 2 widely spaced section pairs of lines are mutually crossed to avoid the undesirable induction. The location of train is represented of gray code. If it is represented in binary code, at the boundary section the plural bits are changed and the undesirable binary code is transitorily generated.

The specification of location detection is as follows:

(a) Detection method:
signal level detection

(b) Level recognition:
variable slice level to basic pair

(c) Received carrier frequency:
128 KHz ±0.12 KHz

(d) Input sensitivity of receiver:
-10dBm ~ -50dBm

(e) Accuracy of detection:
1 meter

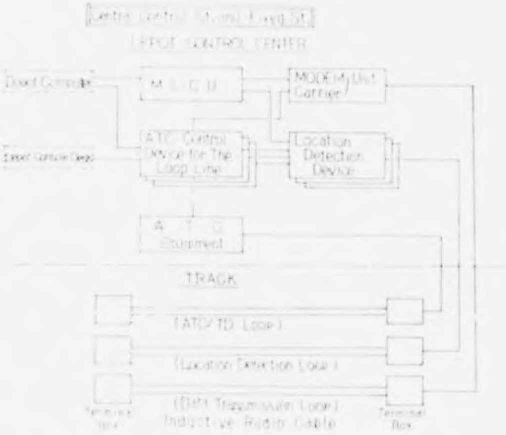

DEPOT CONTROL CENTER
Depot Computer
M C C U
MODEM Unit Carrier
ATC Control Device for The Loop Line
Location Detection Device
Depot Console Desk
A T C Equipment
TRACK
(ATC/TD Loop)
(Location Detection Loop)
(Data Transmission Loop) Inductive Radio Cable
Terminal Box
Terminal Box

Fig.4

(2) Interval control of trains

The loop line around the depot is equipped with ATC devices as one fixed block. Detecting the absolute location of the train, the running direction and interval of trains are observed. When the distance between trains become shorter than the limit, the system controls ATC to stop the train with O_2 code. These processing is carried with one second interval against the trains on this loop line.

(a) In the case of trains run at the same direction or the case of one train runs, the other one stops.

The limit of distance in which the train can stop by emergency braking after it received ATC emergency stop signal is calcurated as the following formulas:

The limit of distance: $L=L_0+L_1+L_2$
The braking distance: $L_0=Vm/7.2\beta$
The running distance before response of braking system: $L_1=Vmxt_0$
The distortion of ditection of train location: $L_2=$ 1 meter
Maximum train speed: Vm (km/h)
Retardation: β (km/h/s)
Delay time of system response: t_0

If the distance between the tail of preceding train and the head of succeeding train is shorter than the above mentioned L, ATC signal must be for emergency stop.

(b) In the case of 2 trains run with facing each other

In this case, if both of trains run at maximum speed, the necessary distance between 2 trains is twice as much as the above mentioned L.

(3) Speed control

On the trial running on the loop line, the maximum speed is 40 km/h on the straight and 15 or 25 km/h on curves whose radius is 30m. To achieve the protection of over speed on curve, ATC codes are controled depending on the location of the train which is calculated at every half second. (Fig.7)

ATC signal up form 15 km/h to 40 km/h is performed just after the tail of train passes through 30m radius curve. ATC signal down from 40 km/h to 25 km/h is performed just before the head of train passes through 30m radius curve.

Fail Safe

Logic system is not the wired logic but the software logic of microcomputer.

To confirm the safety and reliability the hardware is consisted of triplex system, the output is independent of mutual three microcomputers and be decided by majority logic. In case the train's location is not clear or the data transmission from the train is suspended or the microcomputers break down, O_2 code is transmitted to stop the train.

Conclusion

The new ground transportation system "New Tram" has been in commercial operation for three years since March 16, 1981, without serious trouble. So we estimate that the minicomputers and microcomputers are extremely useful and reliable devices, miniaturization of devices, improvement of processing speed are achieved. We hope that new techniques such as moving block section control and data transmission which have not been adopted on the usual railway would become more popular.

Reference

1. Y. Maeda, et al. "Automatic control of Osaka South port town's new transportation system" Japan Association of Automatic Control Engineers (JAACE) presented papers of Vehicle Automation symposium No.3, Jan., 1980.

2. Y. Maeda, et al. "Data Transmission system of New Tram" JAACE presented papers of Vehicle Automation symposium No.4, Jan. 1981.

3. Y. Maeda, et al. "Automatic control system for depot area of New Tram" JAACE presented papers of Vehicle Automation symposium No.4, Jan., 1981.

4. C. Tonda, et al. "Transmission Line for the New Transportation system" Japan Railway Cybernetics Association (JRCA) presented papers of 18th Symposium, 1982.

5. Y. Maeda, et al. "The system concept of automatic operation for Osaka South port town's New Tram" JRCA presented papers of 17th Symposium, 1980.

6. T. Azuma "Control and supervising system of Osaka South port town line New Tram" The Journal of The Institute of Electrical Engineers (IEE) of Japan vol.102, No.1 Jan., 1982.

7. K. Ashiki "On ground equipments and its maintenance for medium capacity transportation for medium capacity transportation system". The journal of IEE of Japan vol. 102, No.1 Jan., 1982.

(a) Principles of location detection

(b) Actual method of location detection

Fig.5: Detection of Train Location

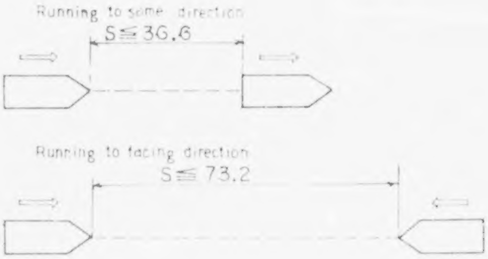


Fig.6: Interval Control of Trains

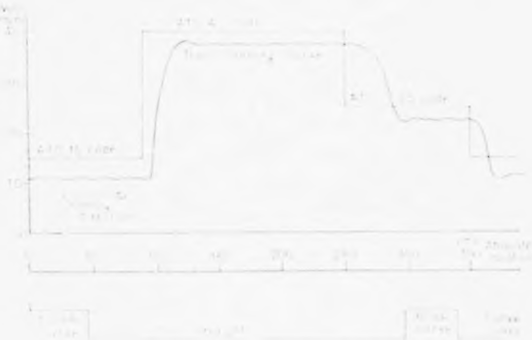


Fig.7: Speed Control Profile

Direction of Transmission	Classification	Contents	Output / Input
Train → Center	Train unusuality information	Train separation, Abnomal door open, Acting of High speed Circuit Breaker	Control Console, PTC, NSPC, Train wireless telephon control
		Break-down of equipment (ATC, ATO, Train wireless, etc.)	
	Train state information	Propelling, Stopping, Automatic operation, Receiving of start command	Control Console, PTC
		Calling	Train wireless telephone control
Center → Train	Intervention Control	Re-starting, Reset of emergency brake, Correction of stopping position	Control Console
	Modification Command	Speed restriction (35 Km/H)	P T C
	Service job command	Automatic announcement	P T C
		ON-OFF of light and air-conditiner	Control Console

note PTC : Central Computer NSPC : Train Number Shift and Display Control unit

AC TRACTION DRIVE ON A PARIS SUBWAY MOTOR CAR

Bernard Esnol,
Schneider Jeumont Rail
West Germany

1 - INTRODUCTION

In April 1980, PARIS SUBWAY AUTHORITY (R.A.T.P) and MTE, CREUSOT LOIRE, JEUMONT-SCHNEIDER Companies decided to fit an AC Traction drive in one of the six hundred MF 77 type motor cars now in operation in PARIS SUBWAY.

The purpose of this experiment is three-fold:

- BOGIES
- TRACTION MOTORS
- TRACTION EQUIPMENT

BOGIES: The bogies are of a new design, manufactured by CREUSOT LOIRE. There are two motors per bogie and the bogie frame is articulated. The half-suspended assembly is more suitable for squirrel cage type motors.

This overall design allows the use of easy-built components. The bogies give good ride quality on sinuous lay-out networks with many low radius curves and warped tracks. A detailed description is provided in Appendix I.

MOTORS: The four motors are 3 PHASES, 4 POLES induction motors (squirrel cage type). The continuous rating is 125 KW.

They are manufactured by MTE-JEUMONT SCHNEIDER. Maximum speed is 5250 REV/mn at 100 km/h. The construction is compact and sturdy.

TRACTION EQUIPMENT: The traction equipment consists of a combination of chopper and inverter built by MTE-JEUMONT SCHNEIDER.

The motor car is provided with 2 chopper/current source inverter units feeding each of the two motors of a bogie. The choice of such a circuit is both ambitious (asynchronous motors in parallel connected) and wise (step down chopper used to reduce the adverse effects on signalling circuits).

The all-up weight of the prototype motor car is very close to the weight of the conventional MF77 motor car, and the performances are identical. This motor car is coupled in a 5 cars train with 2 trailers and 2 other motorcoaches fitted with standard DC choppers designed and manufactured by MTE-JEUMONT SCHNEIDER. This motor coach will enter experimental service with passengers in 1984.

2 - DATA ON MF 77 TYPE MOTOR CARS

Advanced motor cars used in PARIS SUBWAY are fitted with conventional iron wheels, MF77 Series consists of:

- Motor cars with driver's cab (second class) M.
- Motor cars without driver's cab (first class) NA.
- Trailers without driver's cab (second class) B.

The train has 5 cars:

M - B - NA - B - M.

The weight of a 5 cars train is 121,500 kg (unloaded) and 177,500 kg (800 passengers load).

- Maximum speed is 100 km/h.
- Maximum speed allowed in operation is 70 km/h.
- Acceleration is 0,81 m/s^2 up to 40 km/h.
- Service braking deceleration is 1,15 m/s^2.
- Supply voltage by third rail is DC 750V (450 to 900V).
- Voltage battery is DC 79 (50 to 85V).
- Auxiliary AC voltage is 250V 2% - 250Hz ±7%.
- Compressed air for brakes supply, doors and pneumatic equipment: 5 to 9 bars.

3 - TRACTION AND BRAKING DIAGRAM

The 4 asynchronous motors of the motor coach are fed by a chopper/current inverter which achieves both traction and regenerative braking.

The 600 C/S chopper supplied by D.C 750V from the third rail delivers a DC current which can be adjusted by control of the conduction ratio.

The current inverter is fed by current coming from the chopper through a smoothing reactor. The current inverter delivers 120 degrees (electrical angle) current pulses, positive and negative, with intervals of 60 degrees with no current. The frequency varies from 0 up to 180 C/s.

The asynchronous motor being not separately excited requires therefore a supply of energy to get its magnetic field. As the current lags the voltage, the switching of current from an inverter leg to the next leg cannot be carried out in a natural way as for standard rectifiers.

It is necessary to use extra voltages, supplied by capacities which are charged during the switchings.

Thyristors TYCP 1,2,3,4,5,6 chop off the DC current supplied by the chopper so as to get 120 degrees current pulses at a frequency set by the control circuits of the current inverter. (0 to 180 C/s)

Capacities C1,2,3,4,5,6 supply wattless energy used for switching. Only two thyristors are on state since each of them conducts the current for 120 degrees.

4 - LOCATION OF EQUIPMENT

The equipment is fitted on the underframe and consists of:

- 1 semiconductor unit.
- 1 smoothing reactor unit.
- 1 filter line reactor unit.
- 1 filter capacity unit.
- 2 switching capacity units.
- 2 high voltage cubicles.
- 1 circuit breaker box.
- 1 bogie control unit.

4.1 - Semiconductor unit

The overall dimensions of this unit are identical to these of the standard unit MF77 type.

It is divided into 2 symmetrical parts, each related to a bogie.

Each half unit consists of 3 compartments (1 central compartment and 2 side compartments).

Each side compartment is divided into 2 parts:

a) All the power semiconductors of the chopper and of the static traction braking switch are mounted in the first part of each side compartment.

b) The current inverter semiconductors are mounted in the second part of each side compartment.

c) Auxiliary inductances used for the chopper and for the current inverter are mounted in the central compartment as well the chopper quenching capacities.

- The bus bar system is fitted at the top of the central compartment.

- Cooling is achieved by 2 motor-fans (centrifugal type).

4.2 - Smoothing reactor unit

This unit is mounted under the frame. The 2 reactors are designed to work at 600 C/s and have no magnetic cores. The axis of the coil is horizontal. The frame containing the reactors is made of non-magnetic metal sheets.

4.3 - Filter line reactor unit

The reactor is designed to work at 1200 C/s (frequency resulting of a 150 degree phase firing of the 2 choppers) and has no magnetic core. The reactor is force cooled.

4.4 - Filter capacities unit

This unit holds 3 capacities as well as the slow discharging resistor.

4.5 - Switching capacities

Switching capacities are in 2 units. Capacities are designed in account of the reactive energy necessary for switching (proportional to the value of the current and to the value of the cross coupling inductances: LI^2). The units hold also the precharging resistors.

4.6 - Miscellaneous equipment

Some high voltage equipment which does not need to be forced cooled such as current transducers, voltage sensors and bar relays, is mounted in 2 H.V Boxes located close to the bogies.

4.7 - Circuit breaker box

The box holds 3 high speed circuit breakers (CRA 1000 type).

4.8 - Logic control unit

This unit consists of 3 racks containing plug-in cards and achieves the following wing functions:

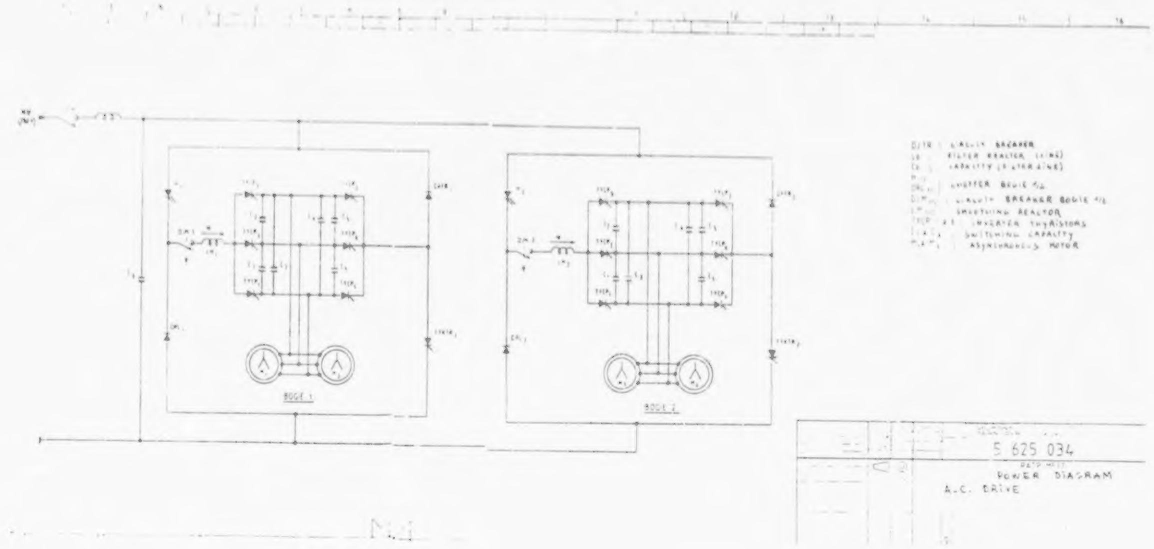
- Supply of the electronic cards.
- Safety control in traction and braking.
- Safety monitoring of the power circuit.
- Load weighing.
- Mechanical brake and energency brake control.
- Brake blending.
- Antiskiding, Antisliding.
- Chopper and current inverter regulation.
- Protection.

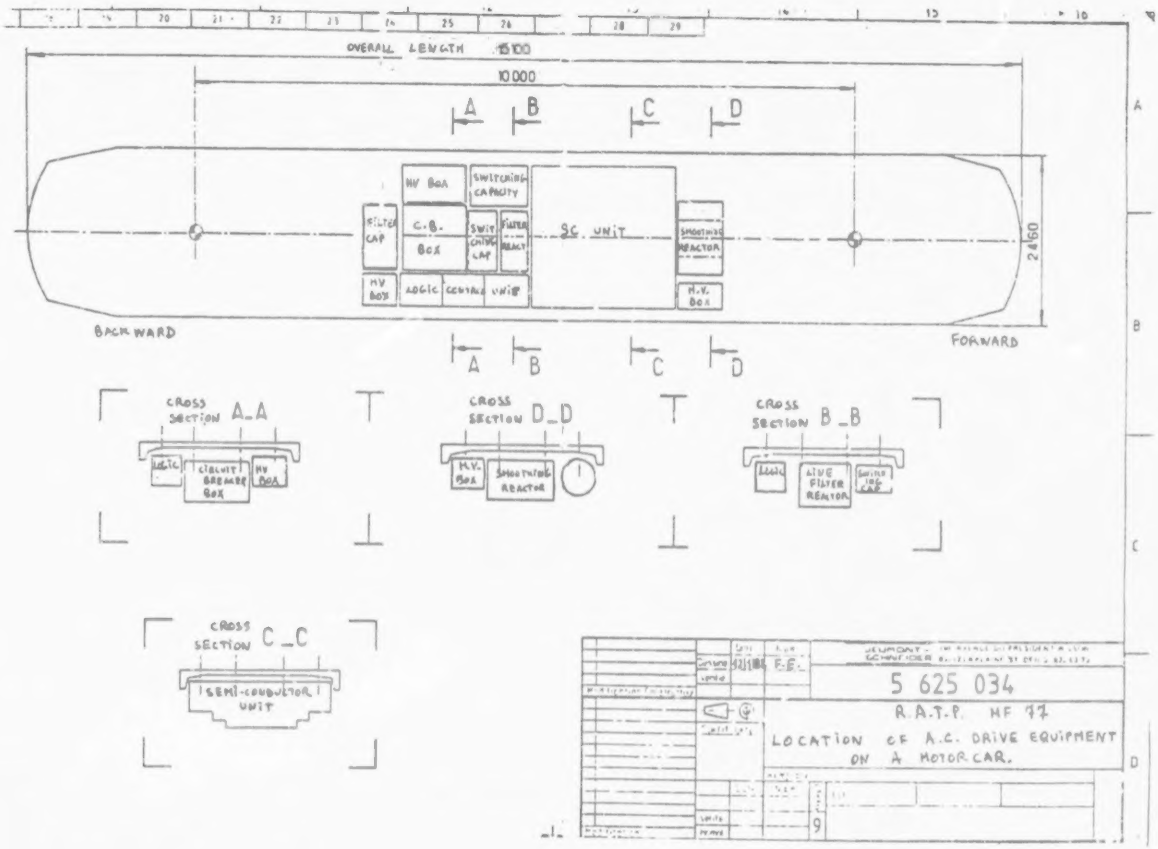
APPENDIX I

Comparison schedules between DC chopper drive and AC drive on a MF 77 type motor car.

Main features	MF77 CHOPPER	MF77 A.C DRIVE
Line voltage	DC 750V	DC 750V
Number of choppers	2	2
Frequency (chopper)	300 C/s	600 C /s
Maximum current supplied by equipment	1050 A	1050 A
Filter natural frequency	36 Hz	75 Hz
Field weakening	static	static through inverter
Traction braking switch	static	static
Electric braking	Regenerative	Regenerative
Reversal	Electromechanical	Static through inverter

WEIGHT (kg)	BOGIES	MOTORS	EQUIPMENT	ALL-UP A.C DRIVE
Conventional MF77	14830	3000	2310	20140
A.C DRIVE	14670	2200	2710	19580


BOGIE 1
BOGIE 2
CIRCUIT BREAKER
FILTER REACTOR (LINE)
CAPACITY (FILTER LINE)
CHOPPER BOGIE 1/2
CIRCUIT BREAKER BOGIE 1/2
SMOOTHING REACTOR
INVERTER THYRISTORS
SWITCHING CAPACITY
ASYNCHRONOUS MOTOR
5 625 034
POWER DIAGRAM
A.C. DRIVE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21
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10
OVERALL LENGTH 15100
10000
A
B
C
D
HV BOX
SWITCHING CAPACITY
FILTER CAP
C.B. BOX
SWITCHING CAP
FILTER REACT
SC UNIT
SMOOTHING REACTOR
HV BOX
LOGIC CONTROL UNIT
H.V. BOX
2460
BACKWARD
FORWARD
CROSS SECTION A_A
LOGIC
CIRCUIT BREAKER BOX
HV BOX
CROSS SECTION D_D
H.V. BOX
SMOOTHING REACTOR
CROSS SECTION B_B
LOGIC
LINE FILTER REACTOR
SWITCHING CAP
CROSS SECTION C_C
SEMI-CONDUCTOR UNIT
F.E.
JEUMONT - SCHNEIDER
5 625 034
R.A.T.P. MF 77
LOCATION OF A.C. DRIVE EQUIPMENT ON A MOTOR CAR.
9

APPENDIX II

ARTICULATED METRO TRUCK WITH ASYNCHRONOUS MOTORS

ABSTRACT

The permanent evolution of rolling stock, the research for better traction performances, better comfort and ride quality have recently led to the development and finalization of new rolling stocks.

Combining the traction characteristics allowed by the JEUMONT SCHNEIDER asynchronous three-phase system, and the high ride quality due to its articulated frame, the truck described hereafter presents a significant step in the metro truck technology.

1/GENERAL - SCOPE OF DESIGN

Some metro networks are characterized by their sinuous or complex track and the requirement to adapt the rolling stock to difficult operating conditions.

That leads in particular to frequent and important variations of the track super-elevation value, the latter having always to optimize the running speed and operating times.

So, in the case of tracks with a sinuous profile, the truck suspensions usually designed in function of comfort, shall also enable to run in areas with super-elevation variation.

These two characteristics are only compatible to the detriment of the load support by each wheel.

In some cases, the weight transfer of wheels would be such that they would no longer guarantee the operating reliability (risks of derailment).

The articulated truck frame, due to its high torsional flexibility enables to limit load variations on wheels, while optimizing comfort.

This type of truck shows very good operating characteristics: comfort and reliability.

View of the truck.

2/TRUCK FEATURES

1 - The frame articulation system

The frame consists of 3 components, 2 equalizers and an intermediate cross-beam, connected by resilient components with the following functions :

- ensure the vertical primary suspension.
- make the longitudinal and lateral connections between the 3 components.
- enable the warping of the assembly in the areas of track with super-elevation variation.

2 - The kinematic chain

The motors are asynchronous, three-phase motors driving each axle by means of a double reduction gear unit and of a special elastic coupling.

This coupling having some flexibility in torsion, is however stiff in the axial plane. Therefore it maintains the motor gear unit in a plane in relation with the axle.

The radial stiffness of coupling hangs the assembly on the axle. The motor nose is itself hung to the intermediate cross-beam of the truck frame.

The latter principle is particularly well adapted to the requirement of hanging the motor gear, while allowing important deformations of truck.

The high specific performances of the asynchronous traction motor, by reducing dimensioning, make the integration of kinematic chain in the truck easier.

3 - Equipment

These trucks are equipped with practically every equipment allowing high performances on modern tracks :

- Truck/car-body rotation roller-bearing thrust.
- Pneumatic secondary suspension with auxiliary reservoirs.
- Hydraulic shock-absorbers.
- Magnetic brakes.
- Wheel-tread cleaners.
- Sanding devices.
- Disc brakes.
- Resilient articulations.

The fabricated structure of this truck allowed while optimizing weights, to reach a high level of reliability.

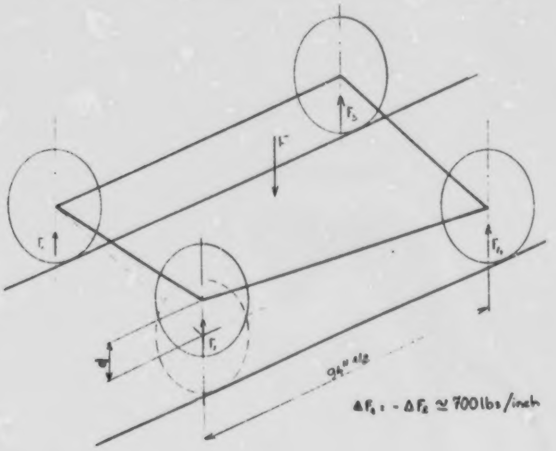
The enclosures attached are a summary of the main characteristics of this truck.

4 - Measurement of torsional stiffness on complete truck

A bench, fitted for this purpose, allowed to measure the load supported by each wheel of the truck, in function of the load on the secondary suspension and a shimming representing the track warping.

These different measurements proved that the load variation per wheel is rather low, that is: on an average ± 500 daN for a 40 mm shimming.

Besides, this flexibility varies slightly with the load condition of car body.



3/TRUCK TECHNICAL DATA

1 - Wheel-Set

The outboard journal axle includes the axle itself, the gear unit hub, the disc brake hub and two wheels.

The total weight of a wheel-set equipped with traction motor gear unit and coupling is 1936 kg.

1.1. Axle

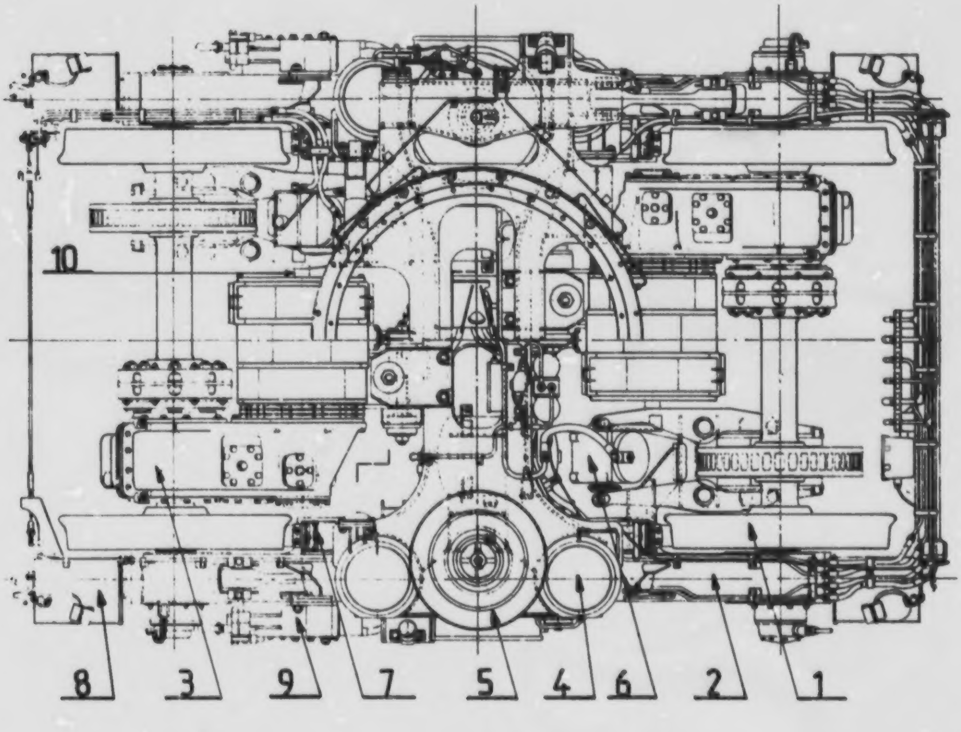
The axle is of annealed semi-hard steel.
Body diameter: 140 mm.
Journal diameter: 130 mm.

1.2. Gear unit coupling

The coupling hub press-fitted on the axle with right orientation in the transverse plane, is equipped with oil assistance for disassembly and by means of a 4 1/4 H tapping.

1.3. Brake disc

On axle, one brake disc (660 mm dia, 110 mm thick) is press-fitted. As a special feature, the disassembly of the outer ring is possible without hub removal.



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Hub disassembly is provided with oil assistance.

1.4. Journal box

The journal box housing is of AF 42 steel in accordance with NF A 33101 Standard.

It includes on its outer surface a groove into which resilient grommets are fitted.

On its front face 8 tapped holes allow fitting of end-axle fixtures.

1.5. Journal bearing

They are of "Cartridge" type, supplied by Timken, designed for 130 mm journal diameter with an outside diameter of 210 mm; they are 132 mm wide.

1.6. Solid wheel

They are of R6 steel according to EM 2824A RATP Standard, rim treated to meet the requirement of ST 301 and UIC 812.3.

- Outside diameter : 860 mm.
- Condemning diameter : 790 mm.

Wheels are sound proofed with NEPURANE coating according to EUROVIB process.

2 - TRUCK FRAME

The truck being of articulated type, its frame shall permit the important vertical displacement of one wheel in relation to the order on a same axle. Therefore the frame was designed for this purpose. It consists of three main parts :

- 2 equalizers resting on the journal boxes by means of resilient grommets around the journal box housings with possibility of conical distortion.
- 1 intermediate cross beam resting on the two equalizers by means of rubber springs acting as primary suspension.

This cross beam connects the two equalizers with some flexibility to achieve the frame distortion.

The truck tram is ensured simultaneously by the four journal boxes and the four resilient primary springs. The intermediate cross beam acts as rigid diagonals for the above square.

The two equalizers and the cross beam are of box section shapes, which gives them high rigidity. These parts are fabricated with A 52 AP steel plates.

3 - PROPULSION

The truck includes two motor-gear units, one for each axle.

Each traction motor is flanged on the lateral side of the gear unit to make a compact assembly fastened in two points on the truck.

The first point is made by a bracket on the front end of the gear unit.

The second point is ensured by gear unit coupling fitted on the axle.

Lateral reactions are supported in the fore traction motor by a resilient rod attached on one end on the traction motor, and at the other end on the intermediate cross beam, and at the axle level by the flexible coupling.

3.1. Traction motors

The JEUMONT-SCHNEIDER asynchronous three phase traction motors have a weight of 550 kg.

They are flange-mounted on a gear-unit.

- Maximum rotation speed	5250 rpm
- Overspeed	6300 rpm
- Starting torque	68,6 mdaN
- Nominal voltage	750 V
- Power	125 KW

3.2. Gear units

Each truck is equipped with two identical gear units.

Unit weight : 432 kg

Each traction motor drives a gear set by means of double convex tooth-gear coupling allowing a slight misalignment.

The gear unit is of two stage type.

The total gear ratio :

$$\frac{49}{18} \times \frac{51}{17} = 8.17$$

is function of performances to get.

The gear casing has a inclined joint face on the slow shaft, in order to achieve dismantling.

The cast casing is of FGS 400.12 cast iron, both gear-couples are of helicoidal tooth.

3.3. Gear coupling

Torque transmission between the gear unit and axle is made by an elastic coupling. The hollow shaft of the gear unit, through which the axle crosses, includes at one of its end a flange into which are fitted 6 pins. These pins drive the coupling hub press-fitted on the axle by means of resilient bushings.

The resilient bushings give to the coupling a conical stiffness which maintains the gear unit in relation with the axle.

The torsional flexibility of the coupling absorbs shocks and filters the vibrations and ensures a flexible transmission traction torque to the axle.

4 - PRIMARY SUSPENSION

The primary suspension is located between the intermediate cross-beam and the equalizers by means of two sets of rubber springs.

This suspension contributes to noise filtration with constant quality life without any wear and with absorption of lateral shocks.

Theoretical thickness of primary suspension per truck is 3080 N/mm.

5 - SECONDARY SUSPENSION

The carbody rests on the truck and rotates on the truck bolster by means of an alternate roller bearing thrust RKS.

The bolster is fixed under the external ring of the thrust. The latter transmits the horizontal forces to the carbody and transmits to the truck with the lateral forces, the vertical forces due to the different loading conditions of the carbody.

Vertical loads are transmitted to double circunvolution pneumatic cushions. Each cushion is fixed in its upper part to the truck bolster and in its lower part to a base resting on the intermediate cross beam.

Elastic bumpers limit the lateral motions. One rigid stop located inside the cushion limits the vertical deflection. However, an elastic bumper starts operating after a 24 mm deflection.

Traction and braking forces are transmitted from the frame to the intermediate cross beam by two horizontal rods equipped with resilient bushings allowing the vertical and lateral displacements of the cross beam regarding to the truck frame. These rods are fitted in opposition at each end of the cross beam.

6 - PNEUMATIC BRAKE

The truck includes two disc-brake units. Each unit located inside the wheel acts on one axle. The total unit including levers, calipers and their friction pads, is mounted longitudinally in the truck. Being fixed to the equalizer, there is no vertical motion between pads and discs. The handbrake acts on one of the two disc brake units.

7 - WHEEL-TREAD CLEANERS

Between the wheels, mounted on the equalizer, the wheel tread cleaner blocks are located.

These blocks compensate the lack of brake-shoes on the wheels and have in addition to their braking action the role of cleaning the wheel-tread to suppress signalling defects by lack of grounding between wheels and rails.

8 - SANDING

There are four sand-boxes are at each end of the equalizers.

Each consists of:

- one box of steel plate, fastened at each end of the equalizer equipped with an inclined opening.
  Box capacity: 11 liters.
- one sand ejector.
- one sanding pipe made of steel, with a rubber sleeve at its end.

9 - CONTACT-SHOES

As usual the truck is equipped with two contact shoes on each side of the truck assembled on a beam fastened to the equalizers by means of adjustable brackets.

A lateral contact shoe may be installed occasionally to allow a car equipped with steel wheels to operate on tracks equipped for pneumatic tyres.

10 - ANTI-SLIP

The slipping of axles is detected by means of impulse generators mounted at the end of the motor-shaft.

This device transfers the information to the electronic box located on the carbody piloting the exhaust valve located on the piping transverse support.

This valve cuts off the cylinder supply and connects them to the atmosphere.

4/ MEANS USED FOR DESIGNING PURPOSES

4.1. Special characteristics of fabricated frame bogies

In the development of technology for the design and construction of bogie frames a marked tendency is developing in the world in favour of replacing cast bogies by fabricated frames.

The reasons are :

- ease of developing the design of the bogies and improving the characteristics with this type of frame.
- lightness of this type of frame.
- ease of manufacture.
- quality and reliability obtained.

Fabricated frame design

The technology of fabricated frames allows for a design without the following limitations of cast pieces :

- frames cannot be cast in less than a minimal thickness, which results in heavy frames.

- design has to be adapted to casting technique. Very expensive mould.

- difficulties in developing frame design. It is difficult to modify a model or a mould without great expense and without risking deterioration in product quality.

The fabricated design allows, on the contrary:

- choice of plate thickness best adapted to the different stresses of each part of the frame.

- precise adaptation of the function and form of the frame to the type of work demanded.

- definition of pieces and placing of necessary reinforcements on the appropriate areas, bringing about distribution of stresses in the complete frame.

- easy and cheap modification of the frame design according to the requirements of the locomotives, e.g. bogie frames for different gauges.

The experience of CREUSOT-LOIRE and their specialization in the design and manufacture of fabricated frame bogies, has enabled their bogies to attain a good level of quality and reliability.

The highly-developed, rational processes of manufacture which are used, particularly in the preparation of the primary pieces, their assembly and soundness, enable the construction of a frame offering exceptional ride behaving in service, high resistance to fatigue and requiring low maintenance costs.

4.2. Calucation of primary suspension equalizers by the method of finite elements

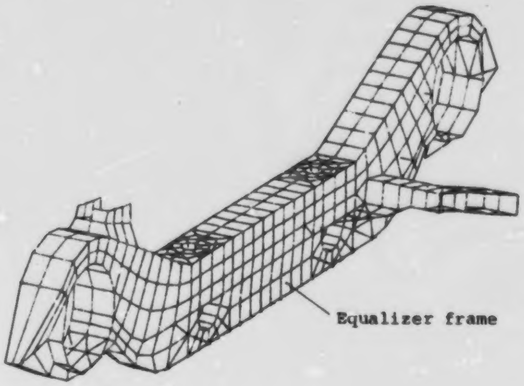
These parts are fabricated box section shapes made of A 52 steel plates which support essentially:

- the vertical loads.

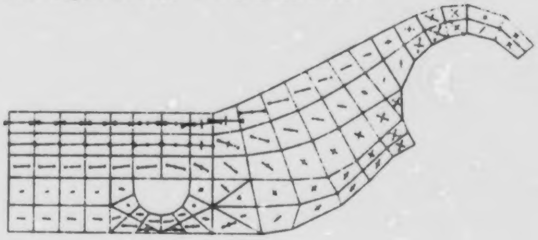
- the longitudinal traction and braking forces.

- the lateral forces.

The calculation allowed to determine the stresses resulting from the different stresses resulting from the different combinations of these loads, and to optimize the technical solutions used for assembly of plates.



Principal Effort 1 3 2 Eche 0.05



4.3. Finalization and testing of gear units

Gear units and couplings equipping this truck were subjected to extensive laboratory tests.

These tests were intended to check and finalize the following:

a) Lubrication and seals.

b) The vibrations and elastic characteristics of coupling or axle.

c) The vibration characteristics of gears and casing.

d) The sound levels under different characteristic operating conditions.

e) The operating temperatures in function of operating cycles.

These measurements were made on a specific test-bench, designed on the basis of two identical gear units in opposition.

Test of gear unit and coupling

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Operational Experience — Bus

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AN INTELLIGENT DATA ACQUISITION AND ANALYSIS TOOL FOR TRANSIT PERFORMANCE MEASUREMENT

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Booz, Allen & Hamilton

James M. Cox
American Computer Exchange, Inc.
USA

Abstract

The San Francisco Municipal Railway operates 345 trolleybuses propelled by switched resistance controlled DC motors (cam). In view of the expanding transit use of variable voltage DC motor controllers (choppers) and the quickly developing interest in variable voltage, variable frequency induction motor controllers (AC Drive), Muni has undertaken a Trolleybus Propulsion Evaluation Project, funded from the Urban Mass Transportation Administration. Two choppers and one AC drive, all commercially available for trolleybuses, will be tested in a Muni trolleybus, as compared to the existing cam-controlled DC motor, for energy efficiency, performance, passenger comfort, and regeneration.

To compare the performance of four propulsion systems of unequal ratings, driven under operator control in varying traffic conditions, an intelligent data acquisition and analysis tool has been developed. For each bus run over a fixed route, the microprocessor-based data acquisition element, called BUSDAC, monitors bus speed; line, motor and auxiliary power; incline; and status indicators; and records the data on cartridge tape. Data are grouped in intervals, called segments, each one of which is the time between each start and stop of the bus.

Data analysis programs, called PLOTPAC, retrieve the run data from the tape; reorder the data into time sequential records for each parameter; perform selected statistical and analytic functions, and provide synthesized reports. In order to permit comparison of average and equivalent travel segments between different pieces of equipment PLOTPAC presents histograms of selected measured and computed parameters for all segments in a run. Histogram results may then be used as an index to the copious segment data. PLOTPAC will provide segment summaries and time plots on command, as well as statistical summaries of the run. Using the data, performance of different equipment operated under similar but distinct conditions can be compared on the basis of statistically validated and selected data.

1.0 Introduction

In San Francisco, the Municipal Railway is one of the nine North American transit properties operating electric trolleybuses. The Muni fleet of 345 trolleybuses is the largest in service, and the number of routes in dense, hilly San Francisco is increasing. The existing fleet of buses are propelled by DC motors with switched-resistance, or cam, controllers.

In view of the expanding transit use of variable voltage DC motor controllers (choppers) and the quickly developing interest in variable voltage, variable frequency induction motor controllers (AC Drive), Muni has undertaken a Trolleybus Propulsion Evaluation Project, funded from the Urban Mass Transportation Administration.

The attractions of choppers and AC drive propulsion systems for transit properties like San Francisco Muni are:

- Advanced propulsion systems use less energy than resistor controlled DC motors when the average travel distance per stop is short. Resistor controlled motors dissipate power in the resistors at low and intermediate speeds.
- Advanced propulsion systems permit controlled regeneration during braking. In San Francisco, the trolley and light rail traction power supplies are coupled together in sections which are extremely receptive to regenerated power. An earlier study[1] predicted that a weekly average of 93.5% of the potentially regenerated power would be received and used in the traction power system. Since up to 30% of the propulsion energy can be regenerated, the potential energy savings to the Muni from general use of advanced equipment would be substantial.

Finally, advanced propulsion systems can provide improved acceleration and jerk performance over resistor controlled motors. Well-designed equipment can also reduce maintenance costs.

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* The work described in this paper was performed under the sponsorship of the U. S. Department of Transportation. The United States Government assumes no responsibility for its contents or the use thereof.

In this project, choppers made by Westinghouse Electric Company and Alsthom-Atlantic Inc. and an AC drive system made by Garrett/Stromberg, will be tested in a Muni trolleybus, and compared to the existing cam-controlled DC motor system. Each propulsion system will be tested for energy usage and efficiency, performance, passenger comfort, and regeneration capability. The test program is being conducted for the Muni by Booz, Allen and Hamilton, with support from American Computer Exchange, of Oakland, CA.

To compare the performance of four propulsion systems of unequal ratings, driven under operator control in varying traffic conditions, an intelligent data acquisition and analysis tool has been developed. For each bus run over a fixed route, the microprocessor-based data acquisition element, called BUSDAC, monitors bus speed and acceleration; line, motor, and auxiliary current, voltage and power; incline; and status indicators. BUSDAC records the data on cartridge tape for off-line analysis. Data are grouped in intervals, called segments, each one of which is the time between each start and stop of the bus.

Data analysis programs, called PLOTPAC, retrieve the run data from the tape; reorder the data into time sequential records for each parameter; perform selected statistical and analytic functions, and provide the synthesized reports. Using the data, performance of different equipment operated under similar but distinct conditions can be compared on the basis of statistically validated and selected data.

2.0 Test Plan

The Trolleybus Propulsion Evaluation Project calls for comparative tests of three advanced, commercially available trolleybus propulsion systems in a Muni Flyer E-800 trolleybus.

The test program is designed to highlight the capabilities of the systems under test in two areas. First, the energy consumption, regeneration, and efficiency of the power controllers and motors will be measured and calculated. Particular attention will be paid to the capability of the equipment to regenerate a maximum amount of kinetic energy into a receptive traction power supply. Note will be made of any situations in which the receptivity of the traction power system is lower than expected. Energy summary statistics will be generated. The second capability of interest is the trolleybus performance, measured in terms of acceleration, jerk, gradability, and schedule performance. In addition, note will be made of any features which impact operations or maintenance of the equipment.

In order to assess the capabilities of the equipment to perform in the Muni operating environment, a test program was established which runs the test bus over three routes, selected to represent the full range of Muni grades and duty cycles. The selected routes are Market Street, with a nearly level profile; Fulton Street, with grades up to 10%; and Union Street, with grades up to 18%. For each route, the test bus will bear an empty, seated, and standing load. Data will be collected during peak and off-peak periods. However, off-peak data collection will be emphasized, since more off-peak hours are available within the limited test schedule. Runs will be repeated to achieve a statistically meaningful, convergent data base, as measured by PLOTPAC summary calculations.

Before data collection begins, the data acquisition equipment is calibrated by making comparisons of BUSDAC readings to independent instruments. For each propulsion system, data convergence tests will be run. In the convergence tests, a subset of a Muni run will be selected in which the operation of the bus can be highly structured. For example, substantial portions of the Fulton and California Street routes are at level grade with regularly spaced blocks. In the convergence data collection, off-peak runs would be made in which the driver attempts to duplicate the same performance for each block-long segment of travel.

During the convergence analysis, the segments which do not represent identical operational conditions will be rejected. Remaining segments will be analyzed for distribution of measured results. Based on the convergence test analysis, a measure of the standard deviation of test results will be generated.

For the first use of BUSDAC, conformation calculations will be made to independently establish the validity of the BUSDAC and PLOTPAC results. These calculations will bracket the results of BUSDAC and PLOTPAC, and will indicate the level of confidence in the analysis results. The confidence level will be used to establish the sensitivity of the analysis results to measurement and calculation inaccuracies.

Finally, at the start and conclusion of each test day, the bus will be checked for integrity of basic equipment and status.

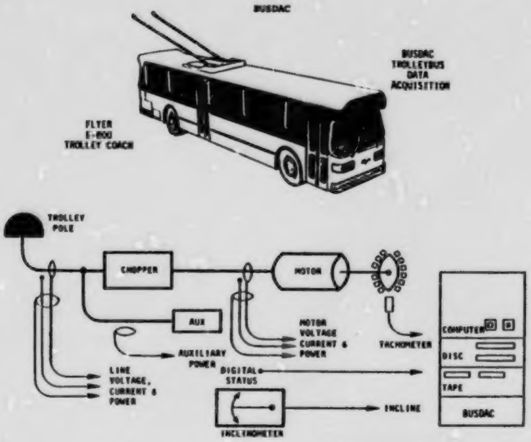
3.0 BUSDAC

The capabilities and performance of the equipment on the test trolleybus are monitored, reported, and recorded by the on-board data acquisition system, called BUSDAC. BUSDAC's connections to the trolleybus propulsion equipment are shown in Figure 1. BUSDAC provides the following capabilities:

- Measure, display and record the bus's operating state, consisting of:
  - Input power, line voltage and current
  - Motor power, motor voltage and current, including AC voltage and currents
  - Auxiliary power

Figure 1

BUSDAC



  - Vehicle speed, from a tachometer, with high resolution
  - Vehicle grade, from an inclinometer
  - Vehicle status, from discrete inputs
  - Acceleration, for jerk measurement
  - Time

o Permit automatic calibration of key parameters, while in the Calibrate Mode:

  - Tachometer pulses per foot, measured by moving the bus a known distance
  - Bus drag force, measured by noting the deceleration of the bus on a level grade with no power applied.

o Record operator's comments in addition to bus data.

3.1 BUSDAC Hardware

BUSDAC is based on a Digital Equipment Corporation LSI-11/23 processor, and includes a floppy disc drive for loading the data acquisition program; a dual cartridge tape drive for recording bus data; a terminal for operator commands and data and status display; and a printer for selective hardcopy. The processor chassis contains the processor, memory, serial communication analog input, digital input, counter/timer, real time clock, and tachometer syncronizer cards.

Bus equipment parameters are measured, isolated, protected and converted to suitable signal levels for the computer data acquisition system by transducers and support equipment. Line, motor, and auxiliary voltage, current, and power are sensed by wide-band power instruments, which represent 600v, 400a power levels by rms equivalent 0-10v signals. The power instruments provide 1% accurate indications for inputs from DC to 5000 Hz. Suitable high voltage fusing and transient protection is provided.

Bus grade is measured by a servo inclinometer, mounted with its sensitive axis oriented in the direction of travel. Grade is calculated by subtracting the acceleration computed from the tachometer from the inclinometer reading. The filtered, buffered output of the inclinometer provides a signal between -10v and 10v DC to the analog to digital converter.

Speed and distance travelled are measured with a tachometer which consists of an eddy current oscillator metal sensor and a 12-toothed wheel mounted to the traction motor drive shaft. The tachometer provides about one pulse per inch of travel. Distance is measured by accumulating tachometer pulses. Velocity is measured by counting 1 Mhz clock pulses for the period of a single tachometer pulse. This approach provides very accurate measurement of velocity at low speeds as well as at high speeds, and yields exact distance data.

Provision is made for up to 16 discrete digital inputs to be monitored and recorded. Eight 600 vdc inputs and eight 12 vdc inputs are fused, isolated and connected to a digital input card on the computer bus.

Data are sampled once per second, except for velocity and position, which are sampled five times per second, and incline, which is sampled ten times per second. Suitable low-pass filtering is provided for analog signals. Based on the selected sampling rates, up to two hours of data can be recorded on the two-cartridge tapes carried in the recorder.

Figure 2 shows the BUSDAC equipment mounted on the test trolleybus.

Figure 2 BUSDAC On The Test Bus

3.2 BUSDAC Software

Busdac software is the computer program that controls the acquisition of data, recording of data, and interaction with the operator. Busdac software is designed to provide a user-friendly environment for the acquisition of data, recording of data, and other functions, such as calibration, initializing of tapes, tape erasing, and test mode.

Busdac software is written in Fortran running under the DEC RT-11 operating system. When the program is running, the operator is offered a series of selection menus on the video screen, and he can request a desired operation by selecting a command using the keyboard. Figure 3 shows the BUSDAC system state transition diagram. Busdac system states are defined by the following operational modes.

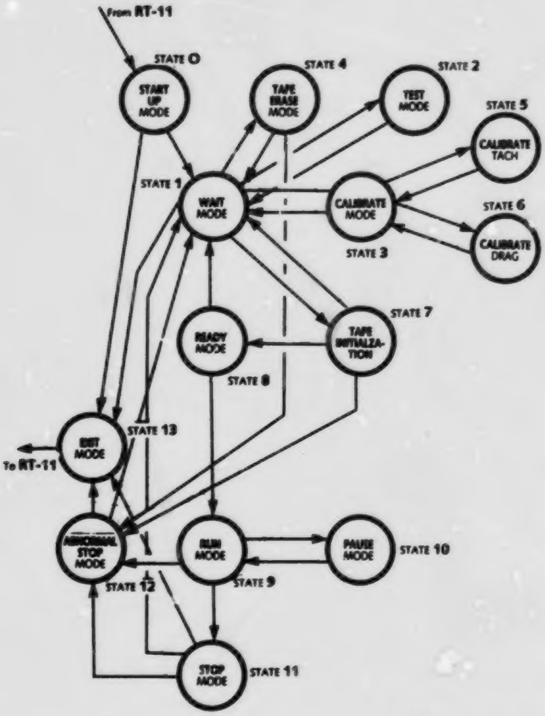


FIG. 3 BUSDAC SYSTEM STATES

3.2.1 Startup Mode

The Startup Mode is entered upon starting Busdac. The Startup Mode requests the time and date from RT-11, initializes variables, outputs a message, and then automatically goes into the wait mode. If there is no system date or time, or if some fatal condition exists, Busdac will exit to RT-11 immediately.

3.2.2 Wait Mode

In this mode, the system displays a menu for selection. The wait mode can transition to the tape initialization mode, test mode, calibration mode, and tape erase mode.

3.2.3 Test Mode

This mode of Busdac operation allows an operator to request the Busdac computer to read and display all sensors every 3.5 seconds. This mode permits an initial checkout of Busdac before a run. The test mode enters from and exits to the wait mode on operator command.

3.2.4 Calibration Mode

In this mode, the operator can inform the Busdac computer that calibration data will be measured. Data associated with the calibration of the tachometer and dragforce will be displayed and printed in hardcopy form. The calibration mode can execute either the tachometer calibration or the drag force calibration by operator command. Both of these modes will go back to the calibration mode upon completion. The operator can then either command Busdac to return to the wait mode or continue with calibration.

The calibration mode also allows the operator to input previously measured tachometer calibration results and/or the previously measured dragforce calibration results and the associated bus weight.

Tachometer calibration is performed by moving the bus a fixed distance, measuring the distance, and entering the result at the keyboard. Dragforce calibration is performed by measuring the deceleration of the bus on a level grade with no power applied.

3.2.5 Tape Erase Mode

From the wait mode, the operator can command the system to go into the Tape Erase Mode. The operator can specify whether to erase only the tape in drive 0 or both tapes. After the tape is erased, the system will issue a message to the operator and will go back into the wait mode. Unrecoverable tape errors will enter the abnormal stop mode.

3.2.6 Tape Initialization

From the wait mode, the system can go into Tape Initialization Mode on operator command. The screen shown to the operator is shown in Figure 4. In this mode, the operator can enter or edit the test run number, number of tapes for this run, route, bus driver's name, Busdac operator's name, bus weight, equipment type, tach and drag calibrations, and an additional comment. This data, along with the date and time (obtained automatically from the RT-11 system), identifies the test run. When the operator has completed desired input or changes, he can issue a command to log the data to the tape. After the system has written the tape, the system will enter the ready mode automatically. Alternatively, the operator can issue a command to

```
System entered Tape Initialization Mode at 12:49:01 01-NOV-83
Select item to change or desired function:
     1. Test run number (0 < nnnnn < 32767):    110
     2. Number of tapes to use for this run (1 or 2): 1
     3. Route:
        MARKET OUTBOUND/INBOUND
     4. Driver name:
        FLINT NELSON
     5. Busdac Operator name:
        ALAN DEGUZMAN
     6. Bus weight (nnnnnn):  32000.
     7. Equipment type:
        CAM CONTROL
     8. Tachometer Calibration (nn.nn):   8.83
     9. Drag Force Calibration (Must match bus weight!) (260.0):
    10. Miscellaneous comment line (70 characters maximum!):
        SHAKEDOWN TEST
    11. Write tape header(s) and go into Ready Mode.
    12. Bypass Initialization and return to Wait Mode.

Enter item number or function number and type RETURN:
```

Figure 4

Tape Initialization Mode Screen Display

bypass the initialization process (before writing to tape) and return directly to the wait mode.

3.2.7 Ready Mode

When tape initialization is completed, the system enters the Ready Mode. From the Ready Mode, the operator can request the system to actually start running (run mode) or return to the wait mode. Returning to wait mode deletes the files created by tape initialization mode, since the header data must be rewritten to get back to ready mode again.

3.2.8 Run Mode and Pause Mode

The Run Mode is the data acquisition and display mode. A typical display screen is shown in Figure 5. It can only be entered from Ready Mode. From Run Mode the operator can request pause mode or stop mode at any time. In the run mode, snap shots of the data being collected will be displayed at regular intervals. This data can be sent to the printer for hard copy by the operator.

The Busdac operator can enter as many comments as desired, of 70 characters or less. The comments are time stamped and recorded.

From the run mode, the system can go into the pause mode and return by operator commands. While in the pause mode, data acquisition is suspended.

3.2.9 Stop and Abnormal Stop Modes

From the run mode, the operator can command the system to go into the stop mode. The system will write out the remaining data and an end-of-data marker to the tape. The system will go into an abnormal stop mode if errors are detected during the run. A message will be given to the operator. Both stop and abnormal stop modes allow the operator to return to the wait mode or to exit to RT-11.

3.2.10 Exit Mode

Exit mode is entered by operator command from Wait Mode, Stop Mode, or Abnormal Stop Mode, or automatically from Startup Mode if startup fails. Exit mode cleans up any outstanding I/O, turns off interrupts that are active, finishes up any housekeeping, and unconditionally exits to RT-11.

```
System entered Run Mode at 16:26:37 10-SEP-83

velocity =                   22.6 mph
distance =                60563.5 ft
incline =                     0.1 degrees
input voltage =             200.0 volts
input current =             198.9 amps
input power =                42.9 kwatts
motor voltage =             200.0 volts
motor current =             199.8 amps
motor power =                39.7 kwatts
aux. power =                 40.4 kwatts
Time: 16:56:40    Date: 10-SEP-83
Status:
  15  14  13  12  11  10   9   8   7   6   5
   1   1   1   1   1   1   1   1   1   1   1

Select desired function:
     1. Accept one comment (70 characters max.)
     5. Enter Pause Mode.
     9. Enter Stop Mode.
Enter function number and type RETURN:
```

Figure 5

Run Mode Screen Display

4.0 PLOTPAC

A set of data analysis programs, called PLOTPAC, provides the crucial capability to convert the collected data into the reduced results necessary for this equipment evaluation project. PLOTPAC was designed to concisely present the results of the analysis, rather than raw data. PLOTPAC analyzes data on the basis of a run, which is defined as operation over an existing Muni route, in this test program. For the purpose of data analysis, each run is viewed as a collection of start-stop-start intervals, called segments. PLOTPAC accepts the data tapes created by BUSDAC, and:

- Calculates propulsion energy usage on an instantaneous and average basis, while calculating velocity, grade, and power use at input, motor, and auxiliaries

- Calculates motoring and braking efficiency, in converting electrical energy to power at the wheels, and calculates the amount of power returned to the power distribution system
- Calculate summary statistics, including:

    - Kilowatt hours used and regenerated
    - Kilowatt hours/Bus mile and Bus hour
    - Average speed and number of stops in test run
    - Average grade and fraction of run on grade.

Like BUSDAC, PLOTPAC is a set of Fortran programs which run under the RT-11 operating system on a DEC LSI-11/23 microprocessor. For the Muni project, two separate microcomputer systems are used to simplify test logistics.

PLOTPAC provides a hierarchy of output results, proceeding from the run summary at the highest and most concise level, to plots of selected variables at the most detailed level. The analyst requests the desired level and amount of reports to be produced for a run, iteratively if required. The purpose of this presentation format is to minimize the amount of raw or processed data provided to the analyst, while still permitting comparison of trolleybus propulsion equipment performance down to the required level of detail.

In this program, propulsion equipment of unequal characteristics and ratings will be manually operated in uncontrolled urban traffic. The limited test schedule and budget will not permit repetition of test runs to guarantee convergence of run summary data over the expected randomly varying factors. Therefore, PLOTPAC was designed to permit rapid identification and selection of equivalent run segments, based on characteristics under comparison. Performance of two pieces of equipment can then be compared over equivalent segments, rather than entire runs. This capability expands the effective size of the data sample, permitting valid comparisons. It permits evaluation of equipment without either controlling the route performance (on a test track) or collecting very large data samples.

After collecting data on a BUSDAC tape, the analysis proceeds as follows:

A run summary is produced by PLOTPAC. The general form is shown in Figure 6.

Figure 6

RUN SUMMARY STATISTICS AND RUN LOG REPORT
RUN xx

```
DATE: xx/xx/xx
TIME: hh:mm:ss
ROUTE: xxx
EQUIPMENT TYPE: xxxxxxxxxxxxxxxxxxxxxxx
WEIGHT: xxxxxxxxx
DRIVER: xxxxxxxxxxxxxxxxxxxxx
CALIBRATION DATA

TOTAL TIME TRAVELING                          = xxxxxxxxx SEC
TOTAL TIME STOPPED                            = xxxxxxxxx SEC
TOTAL TIME                                    = xxxxxxxxx SEC
TOTAL DISTANCE TRAVELLED                      = xxxxxxxxx FT
AVERAGE DISTANCE TRAVELLED                    = xxxxxxxxx FT
PEAK VELOCITY IN RUN                          = xxxxxxxxx MPH
AVERAGE VELOCITY                              = xxxxxxxxx MPH
COMMERCIAL VELOCITY                           = xxxxxxxxx MPH
TOTAL CHANGE IN ELEVATION                     = xxxxxxxxx FT
AVERAGE ASCENDING GRADE                       = xxxxxxxxx %
FRACTION OF SEGMENT ON ASCENDING GRADE        = xxxxxxxxx
AVERAGE DESCENDING GRADE                      = xxxxxxxxx %
FRACTION OF SEGMENT ON DESCENDING GRADE       = xxxxxxxxx
PEAK POWER USED                               = xxxxxxxxx KW
PEAK POWER REGENERATED                        = xxxxxxxxx KW
PEAK MOTOR POWER                              = xxxxxxxxx KW
PEAK MOTOR POWER REGENERATED                  = xxxxxxxxx KW
TOTAL ENERGY DRAWN FROM LINE                  = xxxxxxxxx KWH
TOTAL ENERGY RETURNED TO LINE                 = xxxxxxxxx KWH
NET ENERGY USED IN SEGMENT                    = xxxxxxxxx KWH
NET ENERGY USED BY TRACTION MOTOR             = xxxxxxxxx KWH
NET AUXILIARY ENERGY                          = xxxxxxxxx KWH
ENERGY USED AT WHEELS                         = xxxxxxxxx KWH
ENERGY USED IN MOTOR                          = xxxxxxxxx KWH
ENERGY PER MILE                               = xxxxxxxxx KWH/MI
ENERGY PER HOUR                               = xxxxxxxxx KW
SYSTEM EFFICIENCY                             = xxxxxxxxx
CONTROLS EFFICIENCY                           = xxxxxxxxx
MOTOR EFFICIENCY                              = xxxxxxxxx
PEAK ACCELERATION                             = xxxxxxxxx MPH/SEC
AVERAGE ACCELERATION                          = xxxxxxxxx MPH/SEC
PEAK JERK                                     = xxxxxxxxx MPH/SEC2

hh:mm:ss  RUN STARTS
hh:mm:ss  * SEGMENT 1
hh:mm:ss  COMMENT LINE 1 (max. 70 characters)
hh:mm:ss  COMMENT LINE 2
   .         .
hh:mm:ss  * SEGMENT N
hh:mm:ss  COMMENT LINE
hh:mm:ss  ! DIGITAL STATUS LINE (if any)
hh:mm:ss  RUN ENDS
```

If further analysis or a more detailed comparison basis is needed, segments suitable for direct comparison can be selected using the histogram features. In a histogram, the segments of the run are grouped according to the value of the parameter under analysis, as shown in Figure 7. Histograms can be generated for:

- Distance travelled, average velocity, and average acceleration

Figure 7

PLOTPAC NET ENERGY HISTOGRAM

NET ENERGY (watt-hours)	SEGMENT
0-250	7,9,21
250-500	5,8,19,38
500-750	1,2,3,10,11,12,14,17
750-1000	4,13,15,18,20,24,25,28,30
1000-1250	6,16,22,26,27,33,39
1250-1500	29,34,37,40
1500-1750	36,41
1750-2000	42
2000-2250	
2250-	43

- Change in elevation, and average grade
- Line, regenerated, and net energy usage
- Energy per mile, energy per hour, and system efficiency.

A segment selected for comparison to a segment of another run is described by a segment summary. The segment summary provides the same information shown in Figure 6 for the selected segment. Further, plots of selected parameters versus time may be made for the segment under study. Plots can be generated for:

- Position, velocity, acceleration, jerk, and grade
- Line voltage, current, and power
- Motor voltage, current, and power
- Instantaneous efficiency

Using the analysis results described above, direct comparison can be made of the performance of the propulsion equipment under test in this program. In addition, the capabilities and design of this data acquisition and anaysis equipment allow it to be easily modified or extended to other applications, including transit railcar or electric vehicle performance measurement.

5.0 Reference

1. San Francisco Municipal Railway Receptivity Study; Garrett AiResearch Manufacturing Company, 82-19078, Torrance, CA; August, 1982

6.0 Acknowledgments

The Trolleybus Propulsion Evaluation Project owes its existence and success to many people: Flint Nelson of the San Francisco PUC and Pat Sullivan of UMTA, who managed the project; Alan De Guzman of Muni, who ably built, tested and operated BUSDAC; Ray Louis, Randy Michelson, and Fred Kwong of ACE, who directed and implemented the design; and Jim Mateyka of Booz, Allen, who guided the project along its sometimes hilly path.

DUAL PROPULSION ARTICULATED TROLLEY BUS

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USA

1.0 INTRODUCTION

Dual propulsion vehicles are defined as vehicles having two independent propulsion systems or a single propulsion system that can be supplied energy from two different sources. From an operational point of view, these vehicles are also capable of achieving the same performances and/or operating in either propulsion mode for equal amounts of time. The most commonly found configurations are the following: diesel/trolley, diesel/battery, and battery/trolley.

In recent years, a lot of activity has been observed in several European countries. The development of large-capacity dual propulsion vehicles is being investigated in Finland, France, Germany and Italy. The following section briefly describes their development.

2.0 REVIEW OF THE EUROPEAN DUAL PROPULSION PROGRAMS

This review will briefly describe the status of the various dual propulsion programs in Europe. It will be conducted along the classification presented earlier.

2.1 DIESEL/BATTERY

Often referred to as the "hybrid buses", several demonstration projects are still being conducted in Germany. Prototypes are being operated and/or developed in Japan and Italy. In Germany two different projects involving this configuration were launched in 1979 for a five-year evaluation program (Stuttgart and Wesel). The vehicles are two-axle Daimler-Benz OE 305 models. The battery located between the diesel/generator and the electric motor acts as a buffer.

When running in the hybrid mode, the alternator and the battery provide the energy. When the power demand (at the wheel and auxiliaries) is less than the power delivered by the alternator, the battery is recharged. Even though these buses (20 in total) have operated reasonably well, it was established that the depth of discharge (dod) of the battery was greater than expected (60% vs. 40%). Consequently, the battery needed to be recharged at fixed locations during the day. This reduced vehicle availability and increased cost. In Stuttgart, it was established that where seven diesel buses were previously needed to provide the service ten hybrid buses were now required. The O&M expenditures were estimated to be 30% above those experienced in a regular operation (diesel).

2.2 DIESEL/TROLLEY

This particular configuration has generated a tremendous amount of activity in various European countries. Unlike the propulsion package used as an auxiliary system, this type of vehicle has full performance in either mode. The following discusses the various programs that are presently under way in Europe.

2.2.1 The German Program

The German BMFT (Ministry of Science and Technology) has launched several types of experiments with these types of vehicles. In July 1979, three diesel/trolley prototypes (two standard and one articulated), built by Daimler-Benz entered revenue service in Esslingen. The main characteristic of these vehicles was the absence of the controller of the electric motor. Speed variation of the vehicle was obtained through field control and the regular gear box. This approach was selected to minimize the weight increase of the vehicle (Germany is rather strict with the axle load limit). This scheme proved to be very hard to control because of the differences of inertia that exist between electric and diesel motors. The gear box and the associated driveline elements were put through severe stresses that required development of a sophisticated control system which was never fully demonstrated. Following this experience, the program was reoriented and a new prototype using a chopper was commissioned. This vehicle is both articulated and guided. It is presently undergoing revenue testing in the city of Essen.

2.2.2 The French Program

The development of a full dual propulsion diesel electric vehicle has been completed in France. Today, the city of Nancy is operating a fleet of 48 dual propulsion articulated diesel/trolleys in regular revenue service. This vehicle is derived from the Renault articulated diesel vehicle PR 180. Its main peculiarities are its roof-mounted freon-cooled chopper, its automatic retrieving/raising mechanism, its two driven axles, the solid state dc/dc converter to supply all auxiliary systems, and its central automatic lubrication system. The prototype that was originally built for the city of Nancy has been operated for over one year in the city of Seattle. Recently, LEA monitored the performance tests that were conducted to evaluate the vehicle against three others of the Seattle fleet. While the dual propulsion is not new (from 1933 until 1950 New Jersey Transit operated close to 600 "all service" gasoline/electric vehicles), its reintroduction has been hailed as a new way to improve service, reduce cost and pollution. Several other French cities have this type of vehicle on order.

2.2.3 The Italian Program

In Italy, Mauri, a small body shop, has received funding to develop a diesel/trolley dual propulsion vehicle. The main characteristics of this vehicle are an aluminum body, an air-cooled diesel engine, two driven axles (one in each mode), two continuously variable transmissions (hydrostatic), and no electronic control of the electric motor. The vehicle has been undergoing tests since May 1981. Mauri is known as a bus technology innovator in Italy. (They introduced the first aluminum body and the auxiliary power concept in that country.)

2.2.4 The Finnish Program

In Finland, Stromberg is considering the development of a dual propulsion diesel/trolley with an AC inverter. Presently, 12 trolley buses equipped with an inverter are being operated by the city of Winterthur, Switzerland.

2.2.5 The EEC Program

The various developments observed in Europe have prompted the creation of an EEC committee to evalu ate the various technologies from a technical and economic point of view. All the previously mentioned countries are to provide technical data on their vehicles. Belgium, Denmark and Great Britain are in charge of the economic assessment. The three-year program has now reached mid-course. Testing schedules have been set and were to begin in the fall of 1983. All vehicles will be subjected to a common test cycle. Data acquisition will be carried out with the same equipment which will be loaned to each country. Special attention is to be given to energy consumption. Results will then be analyzed and input to the economic model developed in parallel by the other three countries. The final results of the assessment are not expected until early 1985.

2.3 TROLLEY/BATTERY

Two specific demonstration programs recently took place in France and Germany. The following briefly discusses each approach and the test results.

2.3.1 The French Program

Under a grant from the French Ministry of Transportation, TREGIE, the research arm of Renault Vehicules Industriels, developed a trolley/battery dual propulsion vehicle. Derived from the PR 180, the main characteristics of this vehicle are its chopper and battery pack. The latter is a 160 Ah capacity Nickel-Cadmium battery which was specifically developed for the project. The battery pack underwent two years of testing in different conditions of discharge and temperature. After two years and over 20,000 cycles (at 20% dod), the tests were stopped and judged satisfactory to move to the next phase of the program. The prototype vehicle underwent simulated revenue operation in the city of Lyon, France, under different load and operating conditions. The tests have indicated that even though the vehicle was heavier than a normal articulated trolley or diesel bus the overall energy consumption was reduced. This is due to the fact that the braking energy is systematically regenerated into the battery. At the present time, RVI awaits the commitment of the French Ministry of Transportation to partially sponsor the development cost associated with the construction of ten preproduction vehicles.

2.3.2 The German Program

Under a grant from the BMFT, two trolley/battery buses were built by Daimler-Benz and underwent revenue testing in Esslingen Germany. The poor availability record observed in revenue service has led to the conclusion that this approach was not yet ready for commerical use. The battery used in the program was lead acid.

3.0 THE DUAL PROPULSION TROLLEY COACH IN THE US: THE SEATTLE EXPERIENCE

For several years, Seattle Metro has been interested in dual propulsion operations. High capacity routes combining high grades in the downtown area with high speed runs on the interstate highway system appeared well suited for this type of operation.

In July 1982, under an UMTA grant, Seattle received the first prototype articulated dual propulsion trolley coach (DPTC) ever built by Renault Vehicules Industriels (RVI) for a year long revenue service evaluation. Under this program, the performances of the DPTC, as well as those of three other baseline vehicles of the Metro fleet, were to be established. The three vehicles retained for the comparative evaluation were an AM General diesel, an AM General trolley and a MAN articulated motor bus.

This paper summarizes the findings of this evaluation based on data collected through August 1983.

3.1 THE DUAL PROPULSION TROLLEY COACH

Commonly referred to as the PER 180 H, this DPTC is derived from the PR 180 (diesel only) articulated bus. The PER 180 H is a full dual propulsion vehicle (225 hp DIN diesel mode; 140 kW continuous rating-electric mode). The diesel engine is in-line, rear mounted (after the third axle) and the electric engine is mounted transversely between the middle and rear axles, after the articulation. The electric motor control consists of a main and an auxiliary chopper. The PER 180 H is equipped with a 4-speed (5th on option) ZF transmission with an integrated hydraulic retarder. Regenerative and rheostatic braking are possible in the electric mode. Friction brakes are air activated through three independent circuits. Electric and friction braking are continuously blended.

The PER 180 H is equipped with an automatic pole raising/lowering system. Pole raising can be done only at zero speed at specific locations.

A full rectifier bridge protects the electrical circuit against polarity inversion in the traction mode. A special circuit shuts off regeneration when a polarity inversion is sensed. These features eliminate the need to shut the power off when traversing certain trackworks. Unlike any other articulated vehicles, the RVI PER 180 H has two axles that are driven at all times. This gives the vehicle much greater stability and gradability on poor road conditions.

Forty-eight such vehicles have been operated in revenue service in Europe since November 1982. However, the prototype vehicle now in Seattle has undergone several configuration modifications. These were essentially due to the different operating environments between the two cities. Exhibit 1 presents the vehicle.

3.2 THE EVALUATION PROGRAM

The evaluation of the vehicle consisted of an analysis of the performance of the vehicle and monitoring of the maintenance history while in revenue service at Metro.

3.2.1 Performance Analysis

A test plan was developed to determine the performance of the RVI PER 180 H as well as that of three other baseline vehicles of the Metro fleet. The purpose of the test plan was to obtain data on the acceleration and deceleration characteristics of the vehicle under various conditions of loads and grades.

3.2.2 Maintenance Monitoring

A maintenance monitoring plan was developed so as to gather appropriate data on the problems encountered during revenue service. The items to be monitored included maintenance schedule, maintenance requirements, road calls, cause, frequency, repairs, etc.

4.0 PERFORMANCE TESTING

4.1 TEST PLAN

Originally, the most representative parameters to be measured during testing included the maximum acceleration (uphill and downhill), the maximum deceleration (level and downhill), the time elapsed to reach balancing speed (uphill and level), time elapsed to bring a vehicle from maximum speed to full stop (level and downhill), distance traveled to reach balancing speed (uphill and level), distance traveled to bring a vehicle from maximum speed to a full stop (downhill and level). These parameters were to be monitored under two load conditions -- empty and 130% of seated load -- on various grades (four were selected: 0%, 5%, 8.7%, and 18.5%).

To the extent possible, testing was to be done at the same locations for both trolley coaches and motor buses. This required that actual Metro routes be used. To limit traffic interference, all the tests were conducted in the evening. A test route was sought that would allow operation of the trolley coach between the various grade segments. The anticipated test outputs included the speed/time profiles, the speed/distance profiles, the acceleration/time profiles for each vehicle on each grade under each load condition.

4.2. TEST EQUIPMENT

A fifth wheel and an analog, two-channel, brush recorder were used to record the speed and distance as a function of time. The speed signal was a continuous signal, while the distance signal was recorded through pulses generated every 50 feet. Prior to each test session the speed signal was recalibrated. The distance signal was calibrated at the beginning of the test and at mid-test. Prior to each test run, the distance signal had to be reset to zero manually.

4.3. SUMMARY OF EVENTS

In order to obtain data as comparable as possible, the test segments were selected so that both motor buses and trolley coaches could access them. However, the tests on level road segments could not be conducted at the same location due to the difficulty of finding a section under wire long enough for the motor buses to reach 55 mph. No tests on the 18.5% grade were conducted on the motor buses since they are not specified to run on these routes. To minimize distortions due to driving style, LEA had requested that the same driver be used throughout the tests. During the last two days of testing, the driver of the PER 180 H, who had been made available to us during the previous tests, was assigned to regular runs. Therefore, there were two different drivers each day. Consequently, some test runs were distorted as a result of this change.

Throughout the entire test program, the weather conditions were excellent (warm, sunny weather in the low 70's). Road conditions were unchanged throughout the entire test period and were ideal for testing (dry).

Other than the usual fine tuning of the test equipment, no major problems delayed the tests. On the PER 180 H, a failure of the pulley on the electrically driven compressor required that the air tanks be recharged in the diesel mode.

During the deceleration tests wheel lock-up was experienced twice. On the first day, the right side rear wheels of the AM General motor bus locked during a deceleration test on level. This was attributed to uneven brake adjustment.

On the last day of testing, wheel lock-up occurred on all wheels of the PER 180 H coach during a downhill deceleration test on the 8.7% grade. The vehicle stopped straight and was extremely stable.

4.4 TEST RESULTS: MAJOR FINDINGS

The detailed analysis of the test results indicates that under the given test conditions:

- The AM General trolley coach significantly outperforms the other vehicles. Exhibits 2 through 4 illustrate this point.
- The MAN articulated (newer model) and AM General motor bus have almost identical performance even though the power/weight ratio of the AMG is greater than the MAN's.
- Both trolleys have much better gradability capability than the motor buses, as can be seen in Exhibits 3 and 4.

The results of the test were used to compute the time required to complete the CBD arterial and commuter phase of the ADB operating profile duty cycle shown in Exhibit 5. The results presented in Exhibit 6 indicate that in the trolley mode the RVI PER 180 performs better than any of the motor buses. The other phases of the cycle were not evaluated as they are not found in trolley operations.

In the diesel mode, the dual propulsion trolley coach exhibits poor performance. For example, under empty conditions, the vehicle does not meet either the ADB's requirement for a vehicle at full seated load or the requirements for the articulated trolley coach at 150% seated load as set in the articulated transit coach consortium specifications (see Exhibit 7). This is primarily due to the fact that the test vehicle is a prototype that was designed for totally different operating conditions characterized by a lower service speed -- 7 mph versus 10 mph in Seattle, low percent grades, lower gross vehicle weight, lower maximum speed (37 mph in both modes by regulation).

Even though several modifications were made to the vehicle to improve its operability in the Seattle environment, the basic design constraints still existed. Tradeoffs had to be made. For example, a new electric motor was mounted. Its torque capabilities were almost 50% above the original motor's. However, the new motor could not be used at full torque as the drive train components were not designed to withstand them.

In anticipation of the upcoming dual propulsion trolley coach procurement, RVI and its American subsidiary, Mack Truck, are developing an Americanized version of the vehicle. Among the major modifications would be the utilization of a high torque Mack Truck diesel engine. This new vehicle is presently undergoing test in France.

5.0 MAINTENANCE MONITORING

The higher level of complexity found on Dual Propulsion Buses (DPB's) is likely to require more maintenance to achieve a given reliability goal. Careful analysis of these requirements needs to be performed as they will have an important impact on the overall ecomomics of the project. For example, life cycle cost analyses need to take into account these costs, as well as the higher capital cost of the vehicle. Also one needs to take into account the impact of such vehicles on the capital cost that can be deferred to a later date.

At the present time, only the city of Nancy is operating DPB's under full-scale revenue service. Even though several operational demonstration programs have taken (or are taking) place in the U.S. and in Europe, the data obtained from these should be processed with great care, as they pertain to a very small sample in a controlled environment. These conditions can introduce several distortions which need to be fully understood prior to drawing any conclusions.

5.1 SEATTLE: PRELIMINARY RESULTS

The original schedule called for the performance testing to be completed by January 1983 and to perform monitoring of the DPB maintenance requirements for the entire year. However, due to a variety of problems, mainly technical in nature, the vehicle has not run consistently in revenue service as originially expected. The following section details some of the problems which were encountered.

5.2 ANALYSIS OF THE DPB AVAILABILITY

The availability of the vehicle cannot be easily determined because several modifications were done to the vehicle in order to operate it in the Seattle environment. These modifications were introduced incrementally. Several reasons are at the origin of this approach. Spare parts unavailability and long distance debugging were the major culprits for delaying the introduction of the vehicle in full revenue service. At this point it is important to restate that the vehicle shipped to Seattle was a prototype designed for a totally different operating environment. Some of the major differences between the two types of operations are presented in Exhibit 8. The lack of appropriate documentation and appropriate diagnostic support equipment somewhat amplified these problems.

Over the course of the demonstration, the vehicle was brought to a full revenue operation in five steps. The vehicle now operating in full service is, from a configuration point of view, significantly different from the one that was delivered. The following briefly describes the configuration changes that have occurred at each step.

Configuration Change #1:

From July 19 to about August 15, 1982 about forty changes were made to the vehicle to bring it to Metro standards. A large majority of these changes concerned the vehicle's interior layout, signs, fare box, and modifications of the tail lamps, tires, etc. The impact of these changes was three fold: it resulted in an increase in the vehicle empty mass from 17,200 kg to 19,400 kg, almost 13%. The new tires installed had a diameter close to 20% larger. Consequently, at a given vehicle speed the rotational speed of the electric motor was reduced by the same percentage. The addition of the several electrically powered subsystems increased the average power demand on the low voltage power supply.

Configuration Change #2:

From August 16 to October 31, 1982 the vehicle underwent a series of tests and modifications. Several types of problems were uncovered and solved. The most arduous to resolve concerned the EMI susceptibility of the logic in the acceleration and braking transducers. After a three-week search, it was found that the culprit was a local AM radio station. Metro designed an appropriate filter that cured the problem. As a result of this problem, the vehicle would lose power when driven in the electric mode. The problem worsened as it got closer to the CBD. While investigating several of the possible reasons that could be at the origin of the problem, the reactor of the field chopper burned. The bus was grounded seven days, waiting for a replacement part from France. This problem, which also occurred in Nancy, was due to the poor design and manufacture of the reactor.

The first test run of any significance occurred on September 13, 1982. The vehicle ran 50 miles in trolley mode. However, it was found that the reactor was getting abnormally hot. Propulsion and braking tests in the electric mode were then conducted at full and empty load. It became apparent very quickly that the electric system was overloaded. Several braking resistors burned and the propulsion system overheated several times. After analyzing the problem, TCO concluded that the gear ratio had to be modified to raise the rotational speed of the motor 20%. At the same time, the motor control was modified. In Nancy, where grades are not frequent as well as not as severe as those encountered in Seattle, the field current was boosted 50% above its normal value when the circumstances required it. However, in Seattle, the combination of higher vehicle gross weight, higher grades and lower rotational speed of the electric motor resulted in an overworking of the boosting circuit. As a result, the reactor of the field chopper and the motor field windings were overheating.

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On October 14, 1982 the vehicle was retrofitted with the new gear ratio. As a result of the change, the top speed of the vehicle dropped from 42 mph to 35 mph in the diesel mode and from 37 mph to 32 mph in the trolley mode.

After a successful series of tests, the vehicle was turned over to the instruction department to train the drivers.

In addition to these major problems, the battery and a power steering relay failed.

Due to this modification, the vehicle was able to run in the trolley mode without overheating. However, the performances of the vehicle were severely limited in both the trolley and diesel mode. For example, the vehicle could not, in the electric mode, run on the 18.5% grade on the Queen Ann hill at full load. As indicated earlier, the maximum speed had been reduced in both the trolley and diesel modes.

RVI proposed to modify the vehicle configuration further so as to improve the vehicle's performance. This modification included retrofit of a 5-speed ZF transmission, a new transfer case (T drive), new gear ratio for the differentials, a more powerful electric motor and a more powerful diesel motor. Until these changes were made, the vehicle ran in revenue service on tripper runs.

From November 1, 1982 until January 21, 1983 the Dual Propulsion Trolley coach was assigned to various trolley routes first as a tripper then on a full run basis.

During that period, the vehicle performed relatively well; however a variety of problems were reported. These included power surge problems, T drive problems, recurring problems with the battery, and the relay of the power steering subassembly. Lack of qualified drivers also resulted in missed runs.

Configuration Change #3:

From January 21, 1983 until March 9, 1983, the vehicle was reconfigured to include the new transmission, the new T drive and the new gear ratio in the differentials. During tests in the diesel mode, the diesel engine was put out of commission due to overspeeding. The vehicle had to be grounded until a replacement engine arrived from France. Once the engine was replaced, the vehicle reentered revenue service operation. During that period, trolley operations were interrupted several times by failure of a main fuse. The problem was traced to a faulty integrated circuit on one of the PC boards of the control logic. During the same period, the battery had to be replaced once again. A suspension air bag also failed.

Configuration Change #4:

The vehicle stayed under this configuration from March 9, 1983, until May 31, 1983.

The original power plan reconfiguration which was to retrofit a larger traction motor and a more powerful diesel engine was abandoned. Instead, only the traction motor was changed. Installation of the motor started on March 9, 1983. The retrofit was accompanied with a change of the control logic. This was made necessary due to the different characteristics of the larger traction motor.

As soon as the motor was installed, testing of the vehicle started. Within a few minutes, the propulsion system failed. It was determined very quickly that improper mounting of the motor had resulted in excessive loading on one of the bearings. Renault shipped a new motor.

After installing the new motor and conducting several days of testing, the vehicle returned to revenue service operation. During that period, the static converter failed again. Other failures included the microprocessor controlling the transmission, the batteries, and front door problems. Repeatedly the main fuse blew. This prompted an action by Renault to identify the cause of the problem. After several days of arduous diagnosing, a faulty transducer was found. After repair and testing, the vehicle was returned to revenue service. Shortly after, the electric propulsion system failed again. A main fuse had blown again. A burned spot was also discovered on the cover of the propulsion system. An investigation of the problem revealed that the main chopper had failed and needed to be replaced.

Once again, the time required to acquire spare parts played a major role in the grounding of the vehicle. Also, on several occasions, the lack of drivers resulted in non-usage of the vehicle.

Configuration Change #5:

A new chopper was mounted on the vehicle. This production model included several changes to solve some of the problems that were either encountered in Nancy or Seattle. Following this change, the vehicle returned to revenue operation.

However, surging problems were still present. After a long and painful search, the origin of surging was located. It appears that the mounting bracket holding the SCR was able to slightly rotate. As the ground/high voltage clearances are very small within the freon container, arcing would occur and generate the traction surges. It was also found that an earlier modification to the support brackets of the chopper package could result in the line voltage being applied to the control logic.

Modifications preventing rotation of the SCR mounting brackets and to the chopper package brackets were performed in early September. Since then, the vehicle has consistently run in excess of 100 miles per day. The vehicle is now scheduled seven days a week and is operated the entire day.

5.3 AVAILABILITY: SUMMARY OF THE RESULTS

Exhibit 9 summarizes the overall observed vehicle availability since November,1982. It should be noted that a small fraction of the vehicle grounding was due to the lack of properly qualified drivers.

6.0 CONCLUSION

At the time of this writing, October 1983, Seattle Metro reported that the vehicle was running 13 hours a day, 7 days a week. Dual propulsion operation was satisfactorily demonstrated in revenue service for several weeks.

Overall it took about one year of effort to bring the reliability of the vehicle to an acceptable level. This long time reflects several factors that compounded their effect: the vehicle was the first prototype built by Renault; documentation was scarce and somewhat unreliable as many undocumented changes occurred. The Seattle operating conditions were so different then Nancy's that the entire propulsion package needed to be redesigned. The freon-cooled chopper installed on the vehicle was the first one built by TCO. Several of the features that were noted during the evaluation were directly related to the infancy problems. Spare part availability and lack of appropriate diagnostic equipment often led to grounding the vehicle for several days until the parts arrived.

The prototype now operating in Seattle still has some limitations, especially in the diesel mode. To paliate these, and in anticipation of the furture Seattle needs, an RVI vehicle was retrofitted with a high torque engine. This vehicle is, as of October 4, 1983, being tested in France..

At the outset of evaluation, the major lesson to be retained is that troubleshooting and improvements are hard to accomplish during a revenue service evaluation. It is likely that many of the problems experienced would have been eliminated if the vehicle had been configured and tested to operate in Seattle prior to being shipped.

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BIBLIOGRAPHY

"All Service Vehicle", Rollsign, Special issue, Volume 9, No. 5, May 1982.

Bamberg, W. and D. Dunoyé. "Assessment of the European Dual Propulsion Vehicles", N. D. Lea & Associates, Inc., (in preparation).

Dunoyé, Daniel. "RVI PER 180 H Articulated Dual Propulsion Trolley Coach - Presentation of the Results of the Performance Tests", N. D. Lea & Associates, Inc., September 1983.

Journées Internationales du Trolleybus, Proceedings Union des Transports Publics, January 1983.

Woo, J.C.H. et al. "Assessment of Battery Buses and Battery Technology", Trans Systems Corp., May 1982.

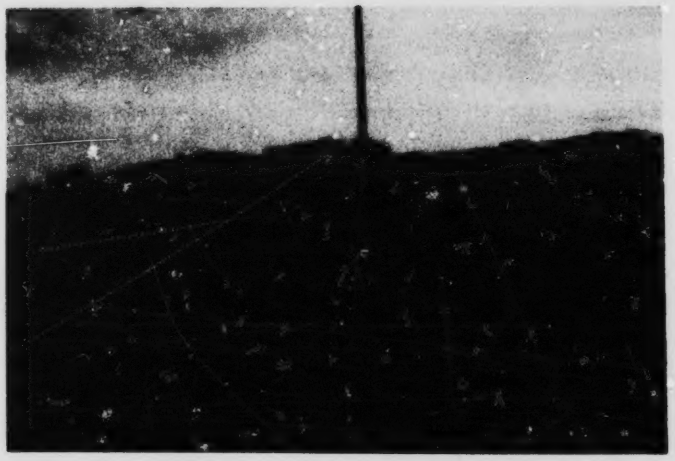

EXHIBIT 1: THE PER 180 H DUAL PROPULSION VEHICLE

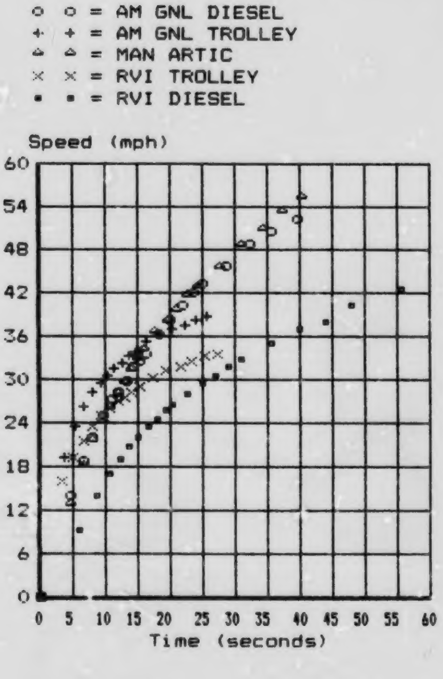

EXHIBIT 2: SPEED/TIME PROFILES 0% GRADE EMPTY VEHICLE

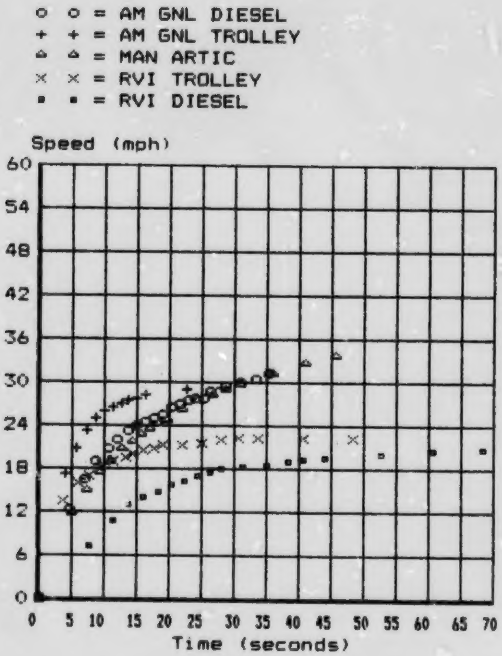

EXHIBIT 3: SPEED/TIME PROFILES
5% GRADE EMPTY VEHICLE

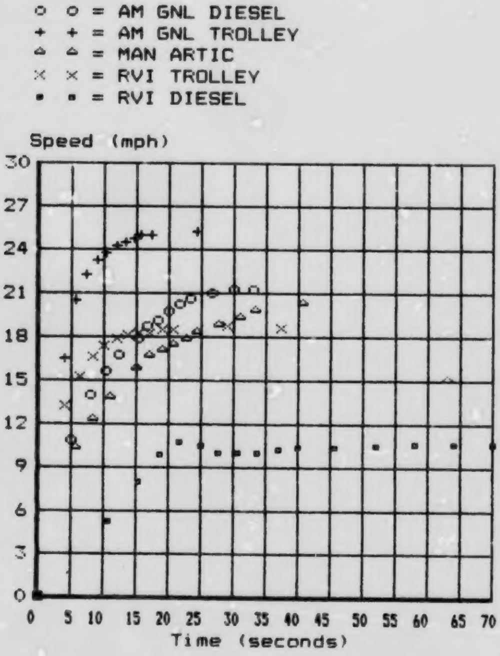

EXHIBIT 4: SPEED/TIME PROFILES
9% GRADE EMPTY VEHICLE

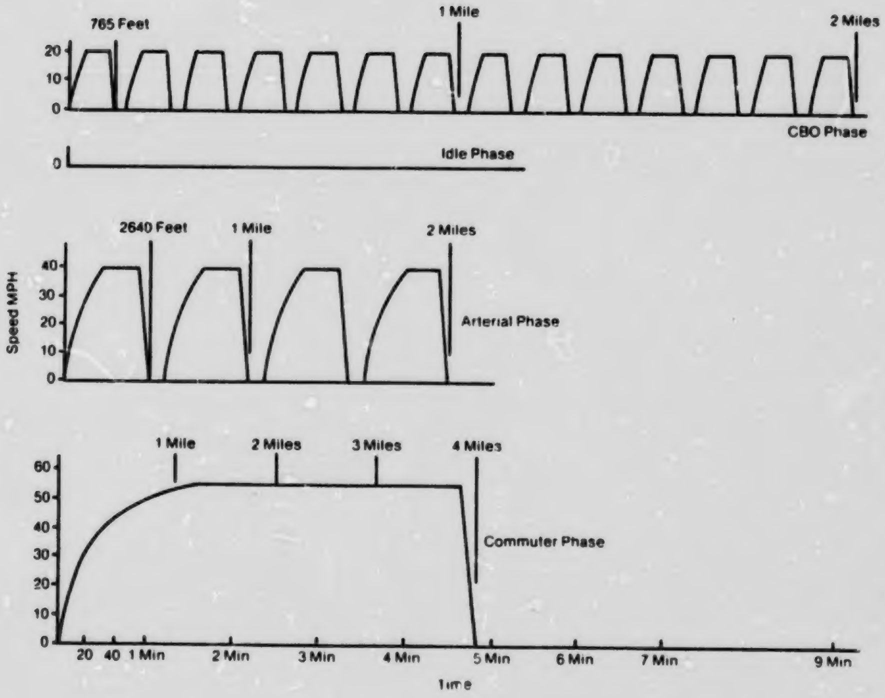

**EXHIBIT 5: ADB OPERATING PROFILE
DUTY CYCLE**

Vehicle	Mode	Load	Cycle			Average speed		
			Urban	Arterial	Commuter	Urban	Arterial	Commuter
AM Genrl	Diesel	140% SC	550.2	276	307.6	13.09	26.09	46.81
AM Genrl	Diesel	empty	543.2	264.4	305.6	13.25	27.23	47.12
AM Genrl	Trolley	151% SC	523.6	NA	NA	13.75		
AM Genrl	Trolley	empty	520.8	NA	NA	13.82		
MAN Arti	Diesel	130% SC	548.8	268	305.8	13.12	26.87	47.09
MAN Arti	Diesel	empty	541.8	262	302.4	13.29	27.48	47.62
RVI PER	Trolley	135% SC	529.2	NA	NA	13.61		
RVI PER	Trolley	empty	518	NA	NA	13.90		
RVI PER	Diesel	135% SC	592.2	(1)	(2)	12.16	(2)	
RVI PER	Diesel	empty	576.8	290	(2)	12.48	24.83	

(1) Cannot reach 40 mph
(2) Cannot reach 55 mph

EXHIBIT 6: CYCLE TIME COMPARISONS

Source: Articulated Transit Coach Consortium
Specifications (1)

TIME (s)	SPEED (mph)	RVI Diesel mode empty
5	13.9	9
10	20.4	16.2
15	26	22
20	30.4	26.4
25	34.2	29.3
30	37.8	32.4
35	40.4	34.6
40	43.1	36.9
45	45.5	38.7
50	47.8	40.7
72.1		46.2 (maxi)

(1) @ 150% seated load

EXHIBIT 7: ACCELERATION & TOP SPEED REQUIREMENTS

	NANCY	SEATTLE
Supply Voltage	750 v	660 v
Motor Speed Ratio (relative to Nancy)	1	0.94
Average Speed	12 km/h	16 km/h
Grade Statistics		
0-3%	35%	40%
around 8%	15%	20%
above 8%	0%	50%
Vehicle Empty Mass	17,200 kg	19,600 kg

EXHIBIT 8: COMPARISON OF THE NANCY AND SEATTLE OPERATING ENVIRONMENTS

SIMAVAI/GRF

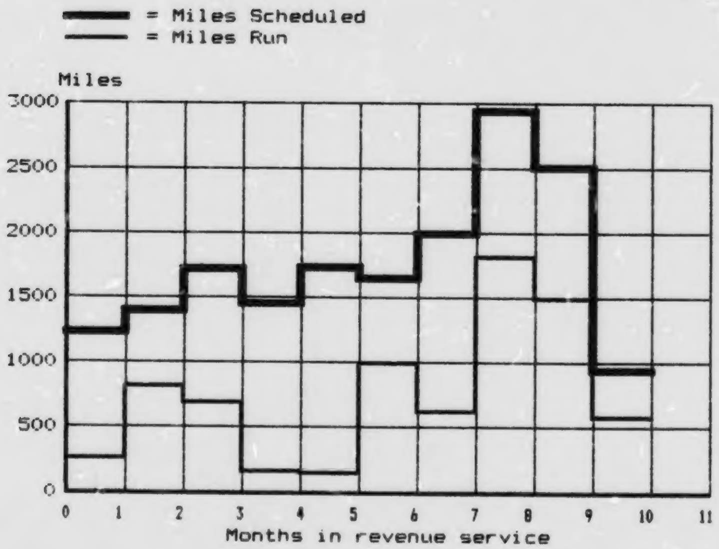

EXHIBIT 9: SUMMARY OF VEHICLE AVAILABILITY (AS OF AUGUST 1983)

OBSERVATIONS ON GUIDED BUS DEVELOPMENTS IN WEST GERMANY

Rolland D. King
Battelle Columbus Laboratories
USA

Summary

This paper describes the dual-mode automatically guided bus developments in West Germany sponsored by the Ministry of Research and Technology that were observed during a tour of European transit systems in May 1983. Information is presented on the mechanical and electronic bus guidance technologies under development by Daimler-Benz and MAN. Descriptions and photographs of the manufacturers' guided bus test track facilities used in the development are also presented. The revenue demonstration program underway in the city of Essen of the mechanical guidance approach; its general status, and the results obtained to data are discussed. Information on guideway and bus guidance equipment capital costs are presented. The author concludes that the technical feasibility of the mechanical guided bus developments has been established and appear to be practical and workable in revenue transit environment. It is suggested that United States transit authorities give careful consideration to this alternative of fixed guideway technology for moderate density cooridors where right-of-way width is important or elevated and/or underground guideways are to be used.

Introduction

In the early seventies, the W. Germany Federal Ministry of Research and Technology (BMFT) began a program with the goal to achieve the high line capacity, high trip speed, and schedule maintenance characteristics of exclusive guideway technologies and yet retain the flexibility of a bus. The dual-mode guided bus developments which are presented in this paper are one of the elements of this research program. The W. German organizations primarily involved in the guided bus program are: R Bosch GmbH, Daimler-Benz AG, Dornier System GmbH, MAN AG, Ed. Züblin AG, Essener Verkehrs-AG (EVAG), and Studiengesellschaft Nahverkehr mbH (SNV). The purpose of this paper is to describe the dual-mode guided bus developments that were observed by the author during a recent group tour of public transit facilities in West Germany.

Background

Of the several approaches considered, two concepts, a mechanically controlled guidance and an electronically controlled guidance have been developed. The mechanical guidance is accomplished by guide wheels attached to the steering linkages of the front wheels of the bus. Both guide wheels are in contact with the guidewalls on each side of the guideway. Whenever the bus approaches one of the guidewalls the guide wheel on that side develops a steering force to return the bus to the center of the guideway. The electronically controlled guidance uses a buried cable to establish the desired course of the bus. An ac electric signal is transmitted in the cable creating an electromagnetic field around it. Antennas mounted underneath the bus detect deviations of the bus from the desired course. These deviation signals are used in the onboard control system to cause a hydraulic actuator, linked to the bus steering system, to steer the bus to the desired course. These concepts were extensively tested in the late seventies at test track facilities in Munich, Rastatt and Stuttgart. Beginning in 1979 the Essen transport authority (EVAG) began the planning of a demonstration of dual-mode guided bus developments in the city of Essen. The purpose of the demonstration was to investigate the feasibility of integrated operation of dual-mode buses and streetcars in the existing streetcar tunnels in the city center. If feasible, this would reduce congestion in the downtown, improve passenger service and convenience and reduce operating costs. The existing tunnels were considered too small for driver controlled operation. Since the tunnels did not have adequate ventilation for diesel bus operations, the demonstration required dual-mode (diesel and electric propulsion) buses.

Bus Manufacturer Test Facilities

Both of the bus manufacturers involved in the program have test track facilities that were constructed to provide a proving ground for their dual-mode guided bus developments. Each of these test facilities are described in the following sections.

Daimler-Benz Test Facilities

The Daimler-Benz Dual-Mode and Guided Bus Test Facilities are located in Rastatt near Stuttgart. Daimler-Benz is developing mechanically as well as electronically guided bus technology. The test track is 3 km long and has curves, straight, elevated and tunnel sections, station platforms with different heights and two types of guideway switches. Photographs of the test track are shown in Figures 1 and 2.

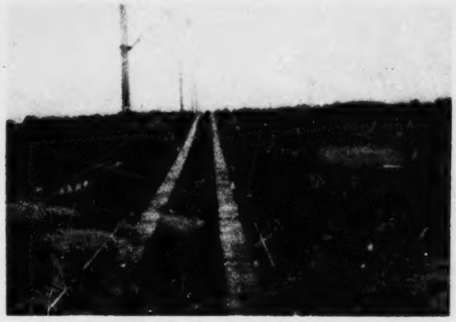

Figure 1. View of Daimler-Benz Guided Bus Test Track Approaching Elevated Section

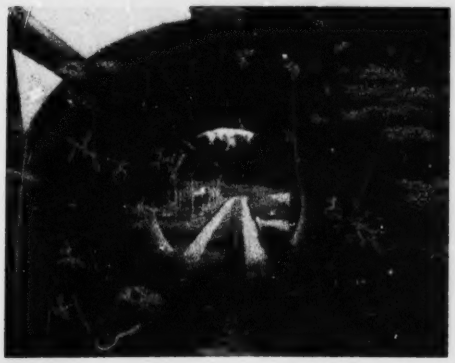

Figure 2. View of Daimler-Benz Guided Bus Test Track Approaching the Simulated Tunnel Section

Daimler-Benz is testing diesel articulated, articulated trolley, and diesel-electric articulated buses at these facilities. The dual-mode bus was developed for the Essen demonstration. In addition, they have developed a double articulated trolley bus that is 24 meters long. It has four doors on each side and requires only a single overhead wire like a streetcar. The ground return is provided by brushes contracting the steel guide rail. (See Figures 3 and 4).

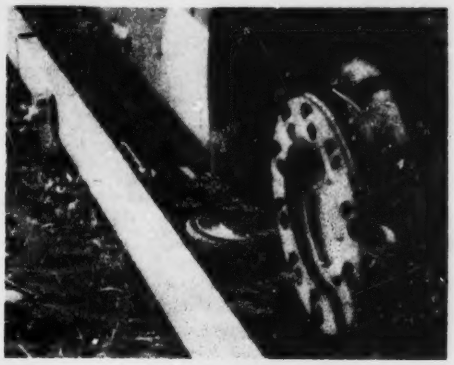

Figure 3. Photo of Contacting Brush Used on Daimler-Benz Double Articulated Trolley Bus

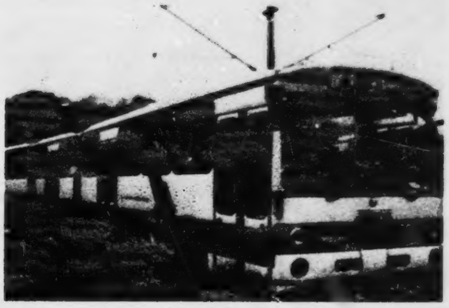

Figure 4. Photo of Daimler-Benz Double Articulated Trolley Bus

Daimler-Benz is using SELTRAC* technology when their guided buses require longitudinal control on the test track. The tour group rode around the test track in several of the buses. The buses performed well in automatic and manual operation. Another interesting development was a mechanism to capture the exhaust fumes of a diesel bus in a tunnel. A slotted guide with a rubber slit runs the length of the test tunnel. The bus exhaust pipe is fitted with an extension that engages the slotted guide at the tunnel entrance. (See Figures 5 and 6) The diesel fumes are carried away by an exhaust fan attached to the slotted guide.

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*A trademark of Standard Electric Lorenz AG (SEL).

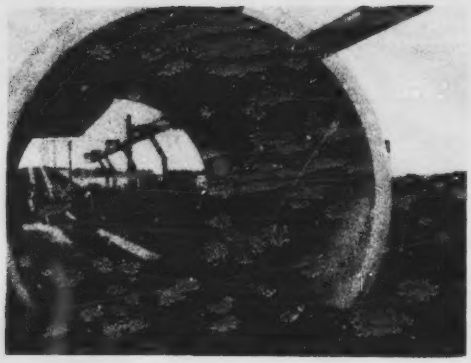

Figure 5. Photo Showing Diesel Bus Exhaust System In Tunnel Section

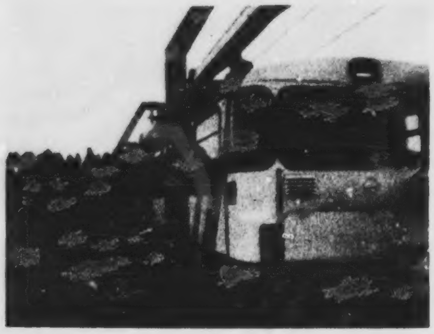

Figure 6. Photo of Diesel Bus Exhaust Pipe In The Slotted Guide

The guideway switches under development by Daimler-Benz and Züblin can be seen in Figures 7 and 8. One raises the straight or curved section of guide rail to guide the bus through the switch. The other concept bends the two guide rails from one switch position to the other and provides a continuous guide rail for the bus to pass through the switch. The lifting edge switch concept has been selected for demonstration in Essen.

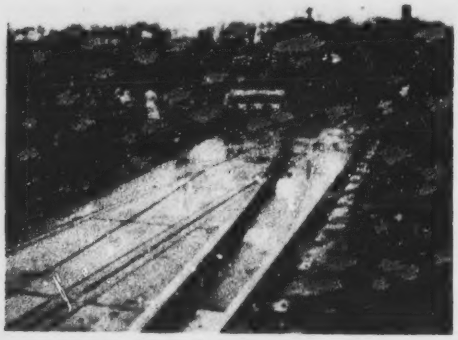

Figure 7a. Photo of Daimler-Benz Guided Bus Switch With Curved Section Raised

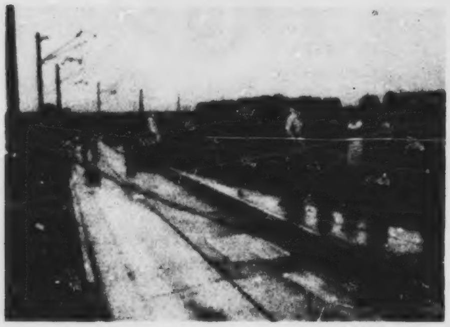

Figure 7b. Photo of Daimler-Benz Guided Bus Switch With Straight Section Raised

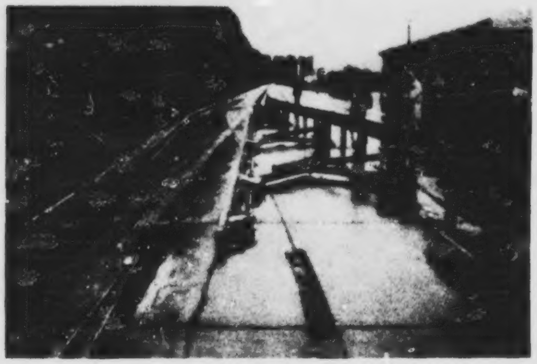

Figure 8a. Photo of Daimler-Benz Flexible Guide Rail Switch Changing Position

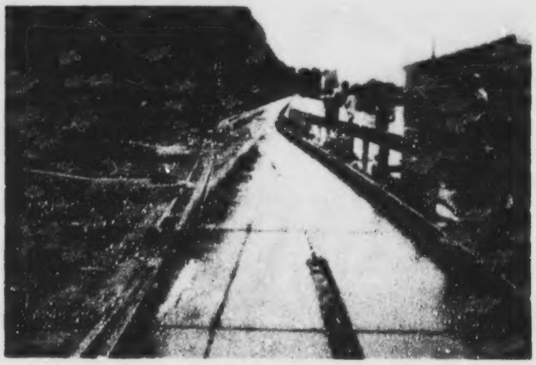

Figure 8b. Photo of Daimler-Benz Flexible Guide Rail Switch In One Of The Positions

MAN Test Facilities

The MAN Bus Test Facilities for guided and dual-mode buses are located near Munich. MAN is developing both mechanical and electronic bus guidance technology. The facility is similar to the Daimler-Benz facilities in that it has straight, curve, elevated and tunnel sections and station platforms with various heights. The track is 3.6 km long and is configured in a large loop with an inner loop that has the elevated and simulated tunnel sections. Photographs of the test track are shown in Figures 9 and 10. The guideway structure for the test facilities was developed by Züblin. The guideway was made up of several construction methods, with most being precast concrete segments about 10 meters in length. In the curved areas, they used the same straight segments, but cast in place a continuous curved inner surface (about 5 cm thick by 9 cm high). See Figure 11. MAN is working on an onboard mechanical switch that would cause the bus to steer (low force) into the left or right guidewall. They do not plan to use any entrapment of the guidewheel. The switch concept was only briefly discussed and was not demonstrated during the author's visit to the MAN facilities. Also, none of the electronic guidance concepts were demonstrated. MAN is testing diesel articulated, articulated trolley and diesel-electric articulated dual-mode buses. The dual-mode bus was developed for the Essen demonstration. MAN also has under development a double articulated diesel powered bus that is 23 meters in length. (See Figure 12.) It has a 280 hp diesel engine located in the rear of the bus and uses a 4-speed ZF transmission. The center two axles are driven and both the front and rear axles are steered. The control for steering the rear axle is taken from the angle of bend of the rear articulated joint.

Figure 9. Photo of MAN Guided Bus Test Track Showing The Simulated Tunnel and Elevated Sections

Figure 10. Photo of MAN Guided Bus Test Track Showing The Station With Several Platform Levels

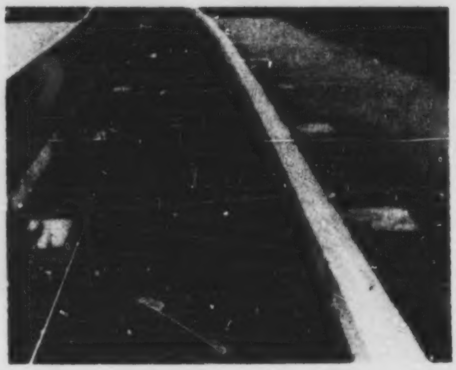

Figure 11. Photo of MAN Guided Bus Test Track Showing Curved Section

Figure 12. Photo Of MAN Double Articulated Diesel Bus

We went through the test track facilities in a diesel powered articulated bus built for Seattle Metro and equipped with mechanical guidance wheels. As you can see in Figure 13, the 102-inch wide bus just clears the simulated tunnel section. The tunnel has an inside diameter of 4.4 meters.

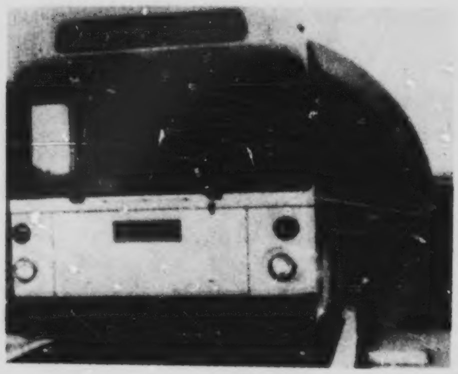

Figure 13. Seattle Metro 102-Inch Bus In The MAN Test Track Simulated Tunnel

Essen Demonstration

As mentioned earlier, EVAG began planning for the dual-mode guided bus demonstration in 1979. The objective of the demonstration is to demonstrate the practical feasibility of combined bus and streetcar operations in their existing downtown tunnels. EVAG chose to demonstrate the new technology in phases, the first phase is a surface demonstration of mechanical guidance and safety control technologies; the second phase is a surface demonstration of combined guideway for streetcar and guided bus, including testing of the dual-mode bus and guideway switch; and the final phase will be a demonstration of combined streetcar and guided dual-mode bus operations in the tunnels.

The first phase began in 1980. The demonstration guideway was constructed on an inactive streetcar right-of-way parallel to Fulerumer Strasse and is about 1.2 km long. The guideway has 3 stations and 3 cross streets. One of the funnel-shaped entrances to the guideway can be seen in Figure 14. The operators had no difficulty in entering the guideway at about 20 mph. They simply steered the bus to touch the left guide rail as they entered; the funnel entrance then narrows so that both guide wheels are in contact with the guide rails. The buses were able to cross the relatively narrow cross streets (about 5 meters) without driver action. See Figure 15. The station platforms were elevated to be level with the first step of the bus as can be seen in Figure 16. A safety headway control system developed by Siemens for buses called "Sicarid" was also being demonstrated in this phase. There are antennas in the guideway that detect the presence of the bus and can cause the brakes to apply automatically if necessary.

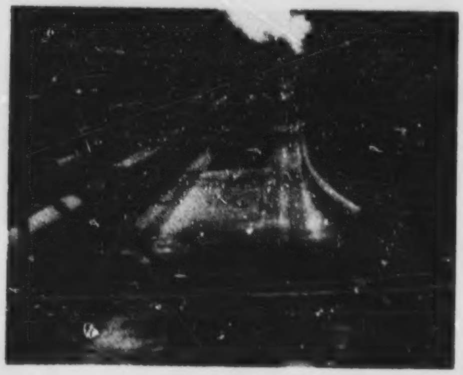

Figure 14. Entrance To Demonstration Guideway In Essen

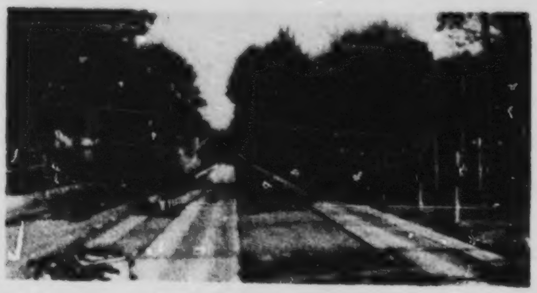

Figure 15. Photo Showing Typical Cross Street Intersection

Figure 16. Photo Showing Station Platform And Bus Interface

The second phase was to demonstrate integrated operation of buses and streetcars on a single guideway. The test guideway is along Wittenbergstrasse and is about 0.9 km long. We rode on the MAN dual-mode bus through this test section on May 5, 1983. Revenue demonstration tests began later that month. In Figure 17 one can see how the streetcar track and bus guideway are integrated. The EVAG streetcars were 2.3 m wide and their buses were 2.5 m wide. You will note in Figure 18 that the rail was placed about 10 cm off center so that the distance between station platform and vehicle step would be the same for buses and streetcars. The integration

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Figure 17. Photo Essen Demonstration Guideway For Both Streetcars and Buses

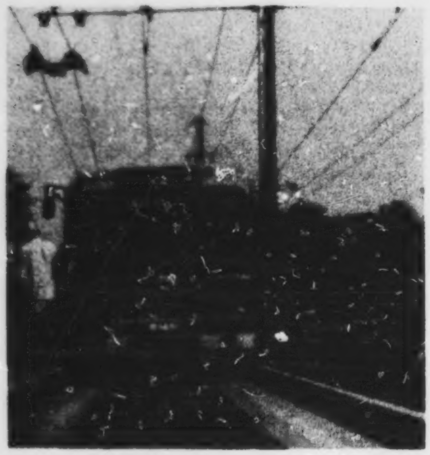

Figure 18. Photo of Station in Essen Demonstration Guideway

of the catenarys for the streetcar and trolley bus can be seen in Figures 17 and 18.

To switch from diesel propulsion to electric, the driver would stop at a predetermined position (usually at a station, see Figure 18.) The driver would then switch to automatic pole deployment. Since the relative position of the two overhead wires is known, a simple funnel device guides the poles to the wires, see Figure 19. The funnels are approximately 30 cm wide and 1 m long. The control for the test switch was being installed at the time of our visit. As you can see in Figure 20 the switch has straight and curved sections of guide rail that are alternately raised by the same switch gear that moves the switch rails.

Some Program Costs/Benefits

We were told that the Ministry for Research and Technology (BMFT) has invested approximately 13 million Deutsch Marks (DM) in

Figure 19. Photo of Funnel Devices Used For Automatic Pole Deployment

Figure 20. Photo Of Test Switch In Essen Demonstration Guideway

the Dual-Mode Guided Bus program. This includes industry R&D, two prototype dual-mode buses, and the Essen Demonstration. In general, the Federal Government sharing of R&D costs in W. Germany is 50:50 for private industry and 75:25 for the transit authority.

For the mechanically guided bus approach, the unit cost for the guideway, at grade, were estimated to be about $500 per meter. The cost to equip a bus with a pair of guide wheels was estimated to be about $2,500.

W. German officials estimated that about 20 to 30 percent construction cost savings can be achieved with an automatically guided bus versus a manually guided bus for elevated or underground structures. The width of the guideway is 2.6 m (2.9 m in total width) as compared to 3.5 m typically used for manually steered bus lanes. This represents about 15 to 25 percent savings in width required for an exclusive bus lane.

Demonstration Experience

The Essen Demonstration Program Manager, Ing. Jochem Boegner, expressed satisfaction with the operational performance of the guided bus technology to date. EVAG has 25 buses equipped with guide wheels. As of May 1983, over 4 million bus kilometers of operation had been reached with no significant wear on the guide wheels or problems with the guideway. The guide wheels have caused no operational problems when the bus is operated in street. The guide wheel arm has a mechanical fuse built in it so that the guide wheel will break off before damaging the bus steering mechanisms. Only one such breakage had occurred as of May 1983. If the guidewheel strikes a curb the bus is automatically steered away which reduces tire abrasion on the curb. EVAG has conducted both passenger and driver surveys and, in general, the technology has been well accepted. During the winter of 1980/81 they experienced some shut downs because of the first heavy snowfalls that occurred after the opening of the test section. A test run was successfully made in a four inch snowfall. EVAG was of the opinion that some treatment (grit or salt) for snow and ice conditions would be required.

Concluding Observations

Based on the author's observations and discussions with the program personnel, the dual-mode guided bus development have demonstrated technical feasibility and appear to be practical and workable in the transit environment. The potential for savings in bus lane width has been demonstrated as well as the integration of bus and streetcar operation in the same guideway. In addition, the guided bus technology enables the use of high-platform stations, thereby, providing the potential for shorter station dwell times in close headway applications. The author believes that United States transit authorities should give careful consideration to this technology alternative for moderate density corridors if right-of-way width is a problem or elevated and/or tunnel guideways are under consideration.

A particularly attractive characteristic is the ability to integrate the bus and rail modes in the same fixed guideway. Usually, communities considering fixed guideway transit have one or two dense corridors and several moderate and low density corridors. The dual-mode guided bus alternative offers the potential of providing the operational benefit obtainable with fixed guideways to more transit riders of the community, thus, providing the benefits of the large investment in fixed guideway facilities to a larger population of the community.

Acknowledgements

The author wishes to acknowledge the assistance and cooperation of Daimler-Benz, MAN, EVAG, and SNV in the preparation of this paper. Special acknowledgement is given to Mr. Ulrich Koch of SNV for his assistance in obtaining information and his helpful review of this paper.

EXPERIENCE WITH BATTERY BUSES AS MALL VEHICLES

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INTRODUCTION

MCR developed Battery Electric Buses have been operating on the Denver Regional Transportation District (RTD) Transitway Mall for more than one year (Figure 1). The Mall is a unique transportation facility which improves bus service, enriches the pedestrian environment and helps alleviate traffic congestion in the downtown area. With two transfer centers anchoring the ends of the mile-long Mall (Figure 2), the specially built shuttle buses are able to travel along the length of the Mall providing congestion free flexibility for persons moving around downtown. In addition, the transfer facilities, used as connection points with the area wide RTD bus service, allow RTD to pull 50 percent of the bus fleet off downtown streets during peak hours, freeing those buses both from the time delays of traffic and the maintenance expense of the stop and go operations. In October 1982, after limited operation for approximately 6 months, RTD placed the 19 Shuttle Buses, developed as a joint venture by MCR and Walter Vetter of West Germany in full service on the 16th St. Transitway Mall. Now, more than one year later it is appropriate to look at the performance of these vehicles to assess the potential for Shuttle service in other Urban areas.

FIGURE 1. DENVER 16TH STREET TRANSITWAY MALL

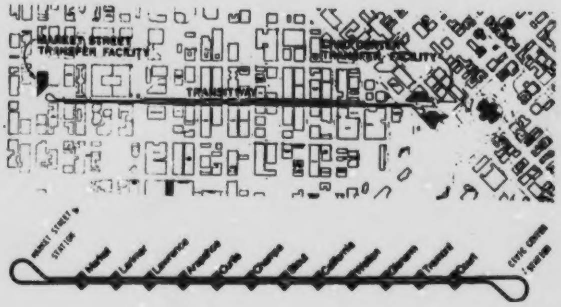

FIGURE 2. MALL PLAN AND SHUTTLE STOPS

GENERAL DESCRIPTION OF SHUTTLE BUSES

The shuttle buses, which were specifically designed for service on the Mall, are 40 feet long, 98 inches wide and have a very low profile and large window area to avoid a massive appearance on the Mall. The driver is seated on the right hand side of the vehicle for unobstructed visibility and to better maneuver the front wheel drive shuttle in the pedestrian environment of the Mall (Figure 3). With three wide doors and a low 12 in. floor to facilitate boarding and exiting and extra large windows for good visibility of the Mall, the shuttles add a new dimension to mass transit. Other features include three popup sunroofs for ventilation and a simple fold out ramp for wheelchair boarding (Figure 4).

Six of the 19 buses in operation are battery powered. The remainder are Diesel powered through an Allison transmission. The battery buses utilize a simple tried and true non-regenerative, chopper controlled, D.C. series traction motor system, very similar to the type used for mine locomotives. A conventional system was used to assure reliable operation in a service that was to start prior to a significant test and development period. Results to date confirm that this approach was appropriate since, although a number of problems have been encountered, they have been systematically addressed by RTD and MCR and have not significantly disrupted service.

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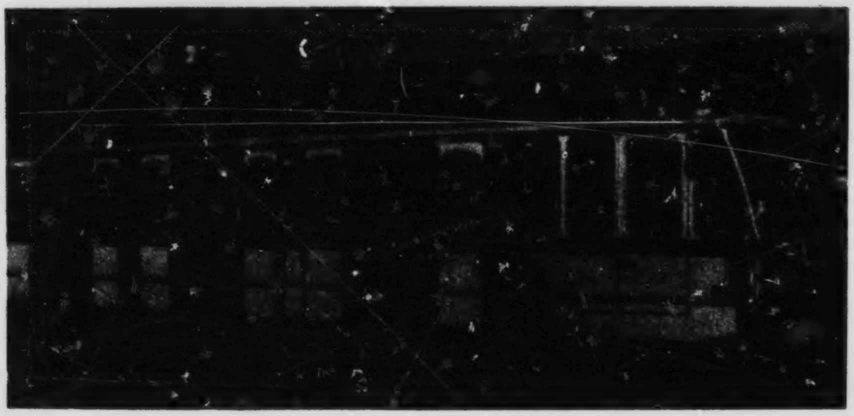

FIGURE 3. MALL SHUTTLE SHOWING RIGHT HAND DRIVE, LOW FLOOR AND THREE WIDE DOORS

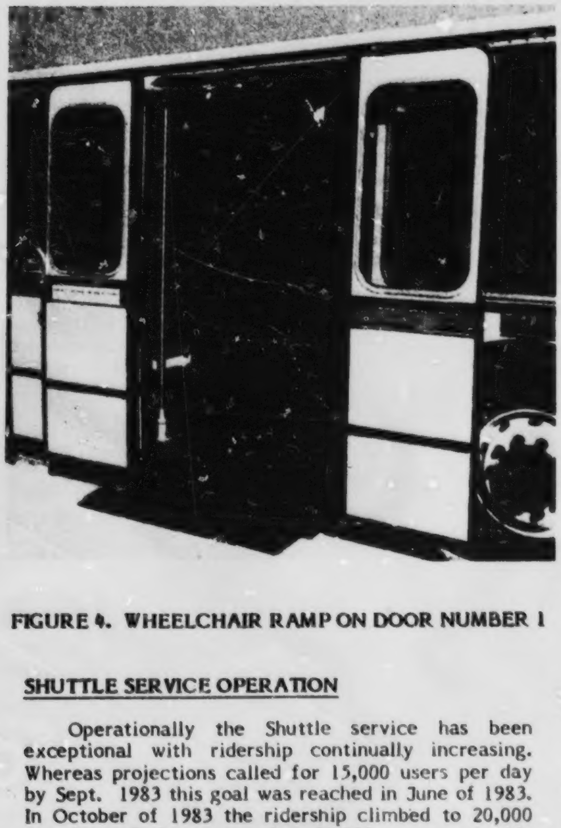

FIGURE 4. WHEELCHAIR RAMP ON DOOR NUMBER 1

SHUTTLE SERVICE OPERATION

Operationally the Shuttle service has been exceptional with ridership continually increasing. Whereas projections called for 15,000 users per day by Sept. 1983 this goal was reached in June of 1983. In October of 1983 the ridership climbed to 20,000 per day. Today, more than 30,000 passengers ride these vehicles during some weekdays and an additional six buses will be added to the fleet to handle the overload and the ridership expected in the following months. During the interim, Articulate Buses are being used to handle the peak hour overflow. Use of these large, high floor transit type buses has dramatically demonstrated the convenience, utility and compatability of the Shuttle Bus design in a pedestrian environment. It is generally agreed by the Denver public that the Mall and the Shuttle Service are assets that have renewed interest in downtown. Merchants in the area have noticed an increase in sales during noontime and have attributed this to shopping by the people employed downtown who find access to the areas around the length of the Mall convenient through the use of the shuttles.

After eighteen months of operation much information has been learned about the use of electric vehicles in an intensive transit environment and in mixed traffic with Diesels. This information will be useful in the design of future mall systems and has pointed to changes that can be made to improve service. The present range of the electric vehicles on the Mall with stops at every station, a full load and a route speed of 7.5 miles per hour is five (5) hours (max. Mall speed is 15 MPH). The original operating plan called for exchanging batteries at the end of 5 hours to continue service. This required a Battery Exchange Facility on the Mall at the Civic Center Station or at the Platt Garage, three miles from the Mall. This facility has not been set up and as a result the Electrics are limited to 4 or 5 hours of operating time per day. This then requires the Diesels to be used all day and the battery buses during peak periods and for fill-in service. With this mode of operation the batteries remain in the vehicles at all times and since they require a minimum 6 hr. recharge after a full discharge, they can be charged only at night. While this is not the service originally intended for these buses, it does provide an opportunity to evaluate them during the most difficult, heavy load periods and in mixed traffic. This demanding operation has provided the stress necessary to reveal some of the weaknesses in the design. For example, during a typical run down the length of the Mall, the driver uses maximum acceleration continuously and opens all doors at every stop. This mode of operation far exceeds the limits used in the design of the propulsion power contactors and the pnuematic system. As a result failure rate on these systems was higher than could be considered acceptable. Changes have been made in these as well as other problem areas which have improved service significantly. In addition recommendations for product improvements have been made to RTD by MCR for improved reliability and to extent the range.

DETAIL DESCRIPTION OF BUSES

The Mall buses are front wheel drive vehicles. All the components and accessories are located forward of the front axle to permit a low floor design. Figure 5 shows a simplified layout of the front end of the Battery Electric Bus. Not shown for clarity are the electronic components; motor controller, power control unit and fuse box, which are located above the equipment illustrated and in the same compartment.

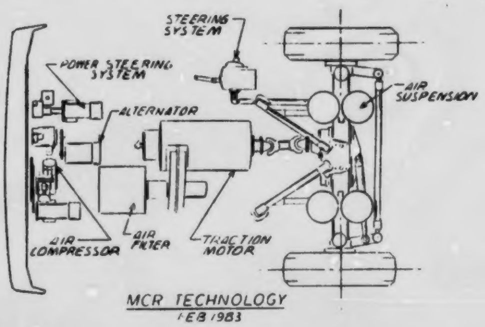

FIGURE 5. PROPULSION SYSTEM AND FRONT AXLE LAYOUT DENVER MALL ELECTRIC SHUTTLE VEHICLE

The alternator, shown in the figure, which is powered from the main propulsion battery by a DC motor, was used to charge the 24 volt auxilliary battery. This system was extremely unreliable and consumed a great deal of valuable propulsion battery power. It has been replaced by a solid state transistorized DC to DC converter developed for MCR by Soleq Corporation. The prototype converter operated flawlessly for more than nine months at more than three times the efficiency of the motor alternator set. During this time the alternator systems in the remaining electrics began failing at an increased rate and a decision was made to retrofit all battery buses with the solid state system. This has now been accomplished.

A continual design problem with large electric vehicles is the need to provide a power steering system which is energy efficient and failsafe. In the Shuttle a compromise is reached in a two step system. A small motor driven pump is used in conjunction with a larger axle driven pump. The axle pump provides hydraulic power when the bus is moving and the motor driven pump is used for low speeds and when standing. After a design change to increase the torque rating of the motor pump coupling this system has operated satisfactorily.

The main propulsion battery consists of four Exide 16E120-19 lead acid batteries (Figure 6) connected in series to produce 128 V DC for the Traction Drive Systen. The total capacity is 1080 amp hours. The batteries are located in four compartments over the wheel wells. Access is through the windows over each wheel (Figure 7). The batteries have performed very satisfactorily in this application.

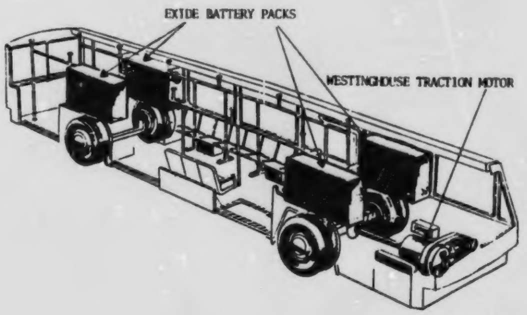

FIGURE 6. MALL SHUTTLE VEHICLE SHOWING BATTERY LOCATION

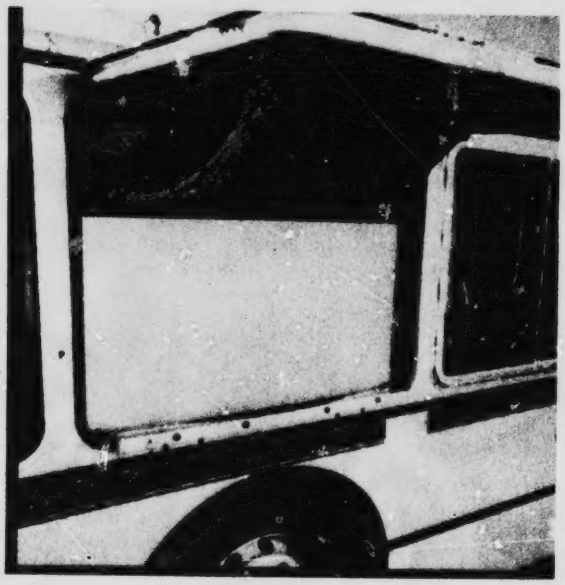

FIGURE 7. BATTERY COMPARTMENT HATCH - FOUR COMPARTMENTS ARE FALSE WINDOWS LOCATED OVER EACH WHEEL HOUSING

The traction system consist of a Westinghouse OX-3612 D.C. series motor, having a peak rating of 150 HP and a continous rating of 65 HP and a Sevcon 1000 amp, SCR chopper controller. Generally speaking, this system has met all performance requirements. However, during the first year of operation the forward-reverse contactors experienced excessive wear. Circuit changes eliminated this problem. Excessive contactor wear was also evident in the chopper by-pass circuit. This was significantly reduced by adding magnetic blow out devices, increasing the contactor size to reduce heat build up, and making circuit changes. Chopper by-pass is used in series motor applications to increase the efficiency of the controller by placing the motor across the battery at the appropriate time. The continuous full out performance demanded by the service is a major contibutor to these problems.

The changes made thus far have improved performance of the vehicles considerably. The main thrust now is to increase the range of the Electrics so they can operate during most of the day. Product improvement recommendations made to extend the range include the Solid State DC to DC Converter for charging the 24 Volt battery (already installed) and a more efficient transistor controlled, separately excited motor system which will also provide regenerative braking. These improvements will increase the range to approximately 6½ hours. In addition, a Hybrid System is under consideration which can meet the goal of full day operation by providing at least 12 hours of continuous operation.

CONCLUSION

In summary, the Electric Shuttle Buses are a new, innovative entry to the stable of transit vehicles. They are attractive, quiet, pollution free and fill a specific need. No other vehicle currently available is more suited to the application. Downtown Denver is alive and growing and part of the reason is the effective transportation system available. The Transitway Mall is an important element in that system. Transit terminals and Malls are not new; you can find them in many cities throughout the world, however, the concept of combining the two is new and Denver should be congratulated for moving forward and sucessfully demonstrating this new approach as a method to assist in the revitalization of urban centers.

Transit EMI/EMC

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THE RAIL TRANSIT EMI/EMC PROGRAM OF THE URBAN MASS TRANSPORTATION ADMINISTRATION AND THE DOT TRANSPORTATION SYSTEMS CENTER

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INTRODUCTION

The UMTA/TSC rail transit Electromagnetic Interference and Compatibility (EMI/EMC) program began in 1979 as a result of the discovery that rail transit chopper propulsion control systems could interfere with audio-frequency track circuits. In response to that discovery, the Rail Transit EMI Technical Working Group (TWG) was formed, with members drawn from signal and propulsion manufacturers, researchers and consultants, and UMTA/TSC. A parallel organization representing the transit authorities and operators was also formed--the American Public Transit Association (APTA) EMC Liaison Board--whose purpose is to bring to bear the experience of transit operators in helping solve EMI problems, and to carry back to the transit operators information on new testing and operating procedures.

Under the guidance and coordination provided by the EMI-TWG, a number of programs of analysis, testing, evaluation, and information dissemination have been conducted to solve specific EMI problems. The primary form of documentation resulting from these activities has been Recommended Practices (RP's) for analyzing and diagnosing EMI, and for assuring EMC. In addition to disseminating RP's, UMTA/TSC has directly provided or arranged for Technical Assistance to transit authorities to aid them in solving specific EMI/EMC problems.

TYPES OF EMI

EMI can affect a transit system by causing both operational problems and safety problems. As an example, inductive interference can cause safety problems. Inductive interference can occur when a rail transit car is directly over a track circuit receiver point. Magnetic fields emanating from solid-state propulsion system components on the car can couple to the loops formed under the car by the rails, car axles, and track circuit receiver leads. Spurious signals induced in the track receiver can cause the track relay to falsely pick up, giving a false clear indication, and causing a direct and obvious safety problem.

Conductive interference can cause either safety or reliability problems. Conductive interference occurs when the audio-frequency or power-frequency components of currents flowing in the third-rail running-rail circuit flow partly through circuit receivers. If this conductive interference leads to the false picking of a dropped track relay, a safety problem results, just as in the case of inductive interference. If the conductive interference causes a track relay to falsely drop, the signaling system will present trains with unneeded restrictions, causing nusiance and reliability problems.

In addition to power-frequency and audio-frequency EMI that is known to affect signaling systems, another potential type of interference has been examined--that of radio-frequency radiated EMI. This potential form of interference has aroused the concern of a number of parties located adjacent to transit rights-of-way, because of the problems that conceivably could occur due to interference with sensitive electronic equipment. In fact, the existence of any actual problem has yet to be documented. However, work on procedures to diagnose and evaluate this potential threat is underway.

INDUSTRY INVOLVEMENT

There are three industry organizations that are active in the EMI/EMC area, in addition to the UMTA/TSC EMI/EMC Program Office, that are instrumental in the identification of needs and the development of RP's.

The first of these organizations is the APTA EMC Liaison Board which meets regularly to discuss the concerns of the transit authorities, nationwide, in the EMI/EMC area. These meetings are attended by members of the UMTA/TSC EMI/EMC program staff. It is here where issues affecting transit authorities were brought to the attention of the EMI/EMC Program Office.

The second organization which is involved with EMC is the APTA EMC Technical Working Group which is responsible for identifying in-depth technical issues concerning rail transit EMC. The members of this group are working technical personnel from transit authorities.

The third industry organization is the TWG. The TWG is composed of senior engineering personnel from a broad range of international transit industry suppliers. These include the suppliers of propulsion systems, signaling systems and traction power substations. All of the activities, including meetings, subcommittee studies, tests and data reduction and analysis efforts are attended and fully supported by transit industry suppliers. The TWG meets regularly at TSC, in Cambridge, and is chaired by the UMTA/TSC EMI/EMC Program Manager. The primary function of the TWG is to examine the concerns of the transit authorities from a technical point of view, and develop Recommended Testing Practices with support from the UMTA/TSC EMI/EMC program staff.

AC Propulsion support, one of the three major areas of program concentration is concerned with the early identification of potential EMI that could result from the introduction of AC propulsion into existing transit systems. Activities in this area include testing of existing signaling systems from the transit authority that will be the test bed for prototype AC propulsion systems. Testing has been conducted in the TSC EMI laboratory and at the field site for the purpose of plotting the envelope of susceptibility of each significant signaling relay circuit to EMI.

In addition, the EMI/EMC program, in support of the TWG, conducts tests designed to develop data that can be used in the construction of analytical models of rail transit systems so that parameters required for the analysis and design of AC propulsion systems can include EMI countermeasures that will assure electromagnetic compatibility. [Studies include rail impedance and single and double rail track circuits.]

The UMTA/TSC EMI/EMC Program monitors EMI testing of STARS AC Propulsion systems that are being developed specifically for use on existing American transit systems. Prototype systems are being developed and monitored in Helsinki, Finland and Pittsburg, Pennsylvania by competing suppliers. When the prototype system is mounted on a test vehicle, further EMI testing will be performed at the Transportation Test Center (TTC) in Pueblo, Colorado and finally on the transit authority test site.

TECHNICAL ASSISTANCE

Technical Assistance is provided to transit authorities by the EMI/EMC Program. When a transit authority discovers a potential EMI problem that could appear on other transit systems, a global problem, or if the technical requirements are beyond the capability of available private consultants, the transit authority, through its Regional Office, can request technical assistance.

Examples of technical assistance provided by UMTA/TSC include the case of a traction power substation generating harmonics that could interfere with ATC signals, creating an operational reliability problem. The EMI/EMC Program staff sent personnel and more than 400 lbs. of EMI test equipment to the site to perform EMI testing. The problem was assessed and data provided to the transit authority. This allowed the authority to retain a consultant to resolve the problem. In addition, the TWG started work on the development of RP's for substations since investigation revealed that several other transit authorities could experience similar problems.

In another example of technical assistance, a new transit authority was facing possible expensive litigation from a major international computer facility. The right-of-way for the transit system ran though the building housing the computer facility and the computer company was concerned that transit operations could cause errors in computer operations.

An EMI/EMC Program team visited the site and met with representatives of the company, building management and building engineers to discuss their concerns. The team developed analytical models of the situation, examined the building structure for absorption of magnetic fields and recommended a series of tests.

Some of the testing was performed by the EMI/EMC team and other tests were contracted out to private industry by the transit authority. The test results supported the EMI analysis performed by the team and indicated that the problems, if any, would be minimal. The result is that the company's computer systems integrity is not threatened and the transit authority will not face expensive litigation procedures.

A third example of technical assistance involves an established system that was experiencing EMI that caused false ATO signals which could have caused safety problems. The EMI/EMC Program staff, working in cooperation with personnel from the transit authority and their signaling supplier, identified the source of the EMI and also recommended several options to overcome the problem.

RECOMMENDED PRACTICES

All the efforts of the UMTA/TSC Electromagnetic Interference and Compatibility (EMI/EMC) Program are aimed at assuring electromagentic compatibility between electronic and electrical subsystems on rapid transit systems. This is accomplished through the development of Recommended Testing Practices (RP's) which are handed off to the public.

These RP's are used in two ways. They may be applied to existing transit systems to identify and characterize problems in electromagentic compatibility, providing data that may be analyzed for the purpose of determining the cause of an interference problem.

Secondly, the RP's can be used in requests for proposal (RFP) as a standard guide to determine that a delivered system meets EMC specifications. We have shown how the need for new RP's can be identified as a result of transit authority concerns brought to the attention of the EMI/EMC program by the APTA EMC Liaison Board and how the problems requiring technical assistance can lead to the development of RP's. Now we will examine the process by which these RP's are developed and who is involved in this process.

Once the need for a new RP has been established the system to be tested is modeled analytically. From this analytical model a draft RP is written. At this point it is reviewed by the members of the TWG. Once the draft has been reviewed and revised as needed, it is taken into the field to a cooperating transit authority. This process is repeated several times, at various participating transit authorities, until the model and test procedures are verified. Then the RP is distributed for comment to the APTA EMC Liaison Board and to APTA members in general. A final document is drafted.

The purpose of the UMTA/TSC EMI/EMC Program, as stated at the beginning of this discussion, is to assure electromagnetic compatability between electrical and electronic subsystems operating on a transit system. Furthermore, we stated that a major objective of the Program is to develop Recommended Practices that can be used by the industry operators, suppliers and consultants, and make these public documents.

This is accomplished by handing off the RP's, when they are verified, to a professional society like the Institute for Electronic and Electrical Engineers (IEEE). The IEEE then issues the RP's as IEEE testing standards and maintains and updates them as required. This then makes available to all interested parties a standard means for specifying performance in the EMC area in RFP's and also an acceptable method for verifying that a finished product or system meets the specified operating requirements.

CONCLUSION

From its inception in response to one specific EMI problem, the UMTA/TSC rail transit EMI/EMC program has increased in scope and activity to assist in the solution of a broad range of EMI problems faced by the transit industry. One result of this activity has been the increased sensitivity within the transit idnustry to the potential for EMI that exists whenever changes in hardware occur, and the requirement for early diagnosis and evaluation of potential EMI problems. Only with such prior attention can the goal of EMC be achieved at the outset of any new transit endeavor.

LONDON TRANSPORT EXPERIENCE WITH CHOPPER INTERFERENCE

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INTRODUCTION

London Transport has been considering the possible consequences of chopper generated interference in signalling circuits for several years, (1),(2). While London Transport does not yet have a fleet of chopper controlled cars, principally due to the long time interval between fleet builds, a great deal of knowledge has been established by practical testing on three prototype chopper equipments and by theoretically based studies, which have been undertaken at the University of Birmingham. The object of this paper is to describe the work to date and summarise the requirements for a system interface specification which could be applied to new chopper equipment.

SIGNALLING EQUIPMENT USED

General Features

London Transport use a 'fourth rail' power conductor system to provide a nominal 630 V dc traction supply. With this arrangement the running rails are normally isolated from the traction positive and traction negative rails and the signal circuits are thus independent of the dc traction return current. This is a significant difference from the more usual 'third rail' or overhead supplied dc systems, where the running rails are used for both traction return and signalling circuits. Historically, design engineers have taken account of this separation to use rail currents for signalling purposes, which are of a much lower value than would be used for similar equipment in other dc railways. On most lines two aspect signalling is used, with a mechanical train stop device to trip a train which overruns a stop signal. On the Victoria Line, trains are automatically operated in response to track based speed commands which are a function of track occupancy and station stop position.

London Transport use 125 Hz based signalling for the control of multiple-unit trains which operate on the surface and in tunnel environments. The nominal 125 Hz signalling power supply, which is generated by motor-alternator sets, may vary from 121 to 127 Hz. For all existing insulated-joint track circuits there is a requirement that a maximum train shunt of 1 ohm should be safely detected. Two types of 125 Hz track circuits are currently used and these are designated as 'capacitor fed' and 'coded' types respectively. For automatically operated trains train-borne safety signalling equipment is used to decode speed commands carried by the 'coded' type of track circuit. In addition to these items, 'delta' type high frequency overlay track circuits are used to provide precise definition of train position in some locations.

Capacitor fed track circuit

The track relay used is a double-element phase-sensitive type which has both track coil and local coils supplied at 125 Hz. The track circuit is supplied at 100V through a series capacitor which is typically 8 μf, to provide the necessary phase shift. The track coil, which may be represented by an R-L series combination with $L \approx 10$ mH, has an input impedance of 8 ohms at 125 Hz. The relay will pick up at 100 mA but the vane will 'move' at frequencies which are close to 125 Hz, for higher values of track current, as shown in Fig.1. At normal values of track current the relay will pick up in 200 ms, but for 125 Hz currents which exceed 500 mA this can be reduced to 40 ms. In plain track areas the track relay contacts are used directly in relay logic circuits. This is different from several railways where 'slow to pick' time delay relays are used to 'follow' the track relay, as the track circuit is cleared.

Coded track circuit

This track circuit is used principally in conjunction with automatic train operation on the Victoria Line. For the track relay to be energised the receiver must detect a 125 Hz current of appropriate magnitude which is full-square-wave modulated at any one of four authentic code rates, which are 2, 3, 4.5 and 7 Hz respectively. This receiver has a minimum operate current of 1A and is relatively narrow band, as shown in Fig.2. For frequencies of interest the receiver may be considered as a resistive circuit, with an input impedance of 8 ohms. Compared with the capacitor track circuit, this coded track circuit operates relatively slowly, the pick-up time being typically 1.0 s, with a minimum value of 0.8 s.

Train-borne safety signalling equipment.

The train-borne receiver detects the modulated track circuit current using antennae positioned above each rail. This receiver essentially consists of a 125 Hz filter which is followed by modulation rate decoding and logic circuits for conversion to traction power and brake control commands. Providing a valid signal is received a relay is maintained and this relay holds off the emergency brake. For a 125 Hz coded track current of 1A, the input receiver stage typically produces 250 mV. The four valid codes are interpreted as follows :

- 2 Hz emergency stop,
- 3 Hz operation without traction power at up to 40 kph (coasting mode),
- 4.5 Hz operation at target speed of 35 kph,
- 7 Hz operation at up to maximum speed.

Delta Circuits

A high frequency voltage source is capacitively coupled to the running rails. The position of the rail connections are chosen such that the circuit inductance and the input capacitor is series resonant, at the supply frequency, when the leading axle of the train is in a specified position. The track feed current is detected by a full-wave rectifier and the output of this detector is used to energise a following relay. There are several styles of delta-circuit in use and the typical supply frequency is 10 kHz.

DISTURBANCE SOURCES AND COUPLING MECHANISMS

Coupling Mechanisms

Signal equipment on London Transport is principally subject to disturbances caused by mutual coupling from the power supply rails. At audio frequencies capacitive coupling from the traction equipment may also be significant. Since the power rails are relatively well-insulated conductive coupling is not normally present and two independent, same-rail, faults are required to produce significant conductive coupling effects. From safety considerations, it is essential that any such disturbance should not be able to produce sufficient in-band signal, of the appropriate form, to cause false energisation of a de-energised signal circuit. In addition it is a reliability requirement that harmonic disturbances in other frequency bands, or transient disturbances, do not cause a normally energised signalling circuit to become de-energised. Theoretical considerations and practical testing, with three types of prototype chopper equipment, have established that the following types of disturbance should be routinely considered for any new application.

Mutual coupling between power rails and running rails. The mutual inductance between the power rails 1,2 and the running rails a,b can be calculated in terms of the relative rail spacing as :

$$m_{ab,12} = \frac{\mu_o}{2\pi} \log \exp \left[\frac{d_{1a}\ d_{2b}}{d_{1b}\ d_{2a}} \right] \text{ H/m} \qquad (1)$$

Practical measurements, over a frequency range of 100 Hz to 2000 Hz, have confirmed that the 'same' track and 'adjacent' track mutual coupling factors of 0.31 μH/m and 0.06 μH/m are accurate to within ± 5%, for track circuit lengths up to 600 m (3). With this form of coupling the voltage induced in a track circuit of length ℓ_{ab} due to a harmonic current I_{12} at frequency ω is given by :

$$E_{ab,12}(j\omega) = j\,\omega\, m_{ab,12}\, \ell_{ab}\, I_{12}(j\omega) \qquad (2)$$

Given that the impedance of the track circuit is known, it is a straightforward matter to calculate the disturbance current for a particular harmonic current in the power circuit from either reliability or safety considerations.

Mutual coupling between power rails and train-borne receivers. Since the antennae which are placed over the running rails are also exposed to the power rails, there is mutual coupling at the input circuits of the train-borne receiver. Since in the London Transport system the traction negative is symmetrically placed between the running rails, this coupling is principally due to current in the traction positive rail which is at the side of the track. The induced voltage in the receiver can be calculated using equation (2) with the appropriate value of mutual inductance for rail to antenna coupling. It will be noted that the train-borne receiver will be routinely subjected to mutual coupling even when operating over a 'balanced' double rail track circuit. In this respect the situation is different from the normal third rail case where series connection of ATP antennae will reject traction ripple disturbance in a balanced track circuit.

Mutual coupling between undercar components and track circuit terminations. During early practical testing it was noted that when the chopper car passed over the relay end of track circuit terminations, the nature of the induced voltage in an artificially occupied track was significantly changed. It was quickly established that this change was due to the external magnetic fields associated with wound components which were undercar-mounted. The levels of induced voltage seen during these tests were relatively small and not significant in terms of operating level for the 125 Hz circuits being tested. However it is clear from other experience in the USA (4) that this effect must be considered when modern type low-power jointless track circuits are considered for possible use in the future.

Electric field coupling between traction equipment and the running rails. Since the power rails are relatively well insulated, the cyclic step changes of voltage, which are characteristic of power electronic equipment, will give rise to repetitive transient currents in the earth return, due to the cyclic charging and discharging of stray capacitances from the power equipment to the car body. These currents will flow in the earthed running rails and will generate disturbance signals. The general principle of this type of disturbance is illustrated in Fig.3. This effect is particular to the insulated rail power supply system and would not be significant in an earthed return railway. From extensive practical measurements it has been established that the transient charging and discharging currents are repetitive at chopper frequency and are associated with step changes of the chopper voltage, particularly in the regenerative brake mode. With the two types of prototype chopper equipment tested so far in two locations, the characteristic frequency of rail current is in the range 8 to 20 kHz, with peak rail current values of 10A. The repetitive transients are exponentially damped, with a typical damping ratio of 0.2. To support the practical measurement programme a theoretical assessment of this effect has been undertaken. Due to the distributed nature of the earth return circuits, it has been necessary to use a numerical based approach to solve the high order differential equations associated with the complex equivalent circuit. An example of the predicted response and the associated frequency distribution for the earth return current is shown in Fig.4. The correlation between practically measured results and the theoretical predictions is quite reasonable and this model has been used to assess remedial measures.

Sources of disturbance current.

Harmonic sources. The harmonic spectrum of the traction return current contains multiples of the mains frequency and the chopping frequency. After an initial assessment of tolerances on mains frequency and signalling frequencies, London Transport selected chopper operating frequencies of 274 or 384 Hz to avoid the possible production of code rate components by 'beating' or intermodulation effects. Due to the inductive nature of the traction circuit impedance, the effect of low magnitude mains frequency components at 50 and 100 Hz (2) are more significant than the characteristic harmonic frequencies of 300 Hz and 600 Hz which are usually associated with 6 and 12 pulse rectifier equipment. It should be noted that half-wave configured rectifier circuits are still in use on some parts of the power supply system.

Transient disturbances due to filter. Due to step-voltage changes at the input filter relatively large exponentially damped sinusoidal current will flow in the power rails, at the characteristic frequency of the line filter/traction return circuit, which is typically 20 - 35 Hz. Due to differences in the closing of line-breakers, measured transients can last for up to 200 ms. Since all harmonics of this current may transiently excite the capacitor fed vane relays at 125 Hz this has been carefully assessed. To date the level of transient 125 Hz energy measured has not been sufficient to move the relay, however if this transient was continuously repetitive then the current would be in the operating region (2).

PRODUCING AN INTERFACE SPECIFICATION.

London Transport often produce prototype cars before a major new fleet build. Since chopper technology for fleet application is now aimed at the replacement of Central Line stock in 1990, there has been adequate time for a systematic approach to defining interference effects and developing the necessary features of an interface specification. This approach has involved :

1) Practical testing and theoretical studies;
2) Assessing the results for existing signalling;
3) Definition of procedures for controlling disturbance current;
4) Generation of specification requirement.

Practical testing and theoretical studies.

Extensive practical testing has been undertaken to assess all the interface effects defined above. At test sites on the Picadilly Line and on the Woodford-Hainault loop, for automatically operated train equipment, the effects of chopper interference have been established by practical measurements, for normal and fault conditions. At each stage of the programme the practical work has been corraborated by theoretical models which were devised at the University of Birmingham. This combination of theory and practice is essential since it is not possible to test for all combinations of parameters and whole fleet conditions. For the theoretical work the general approach is to develop flexible software models. Examples of the models developed include :

- calculation of chopper harmonics for whole fleet conditions;
- calculation of substation harmonics for whole fleet conditions;
- calculation of transient responses for multi-chopper conditions;
- calculation of chopper harmonics with earth fault conditions;
- calculation of electric field coupling effects.

Assessing results for existing signalling.

Capacitor fed track circuit. From safety considerations it is essential that the chopper equipment does not operate within the 125 Hz band, or at lower frequencies which are subharmonics of 125 Hz. Since the relay is not coded, the generation of small values of 125 Hz current in the traction rails (6A) could cause the pick-up of a de-energised relay. To avoid this possibility the chopper frequency must be controlled in a safe manner. From reliability considerations it is necessary to limit the rms current in the traction rail circuit. This implies specifying the input impedance of the chopper equipment.

Coded track circuit. For unsafe operation both carrier and coding are required. As a safety consideration it is considered necessary to limit the operation of the chopper to a defined frequency, as discussed above. Since the 'minimum to operate' carrier frequency signal level is about 10 times greater than for the capacitor fed track circuit, this element is not considered to be critical. In addition the relatively slow pick-up time provides immunity against the transient disturbances associated with charging the chopper input filter.

Train-borne safety signalling equipment. As for the other elements which use the 125 Hz carrier, it is considered essential to avoid the production of 125 Hz component in the supply rails by chopper action. This is particularly important since the antennae will 'see' a traction rail current at about one fifth of the sensitivity for normal running rail currents and the receiver normally operates on 1A in the 125 Hz band. While it is true that the coding provides additional security, the philosophy adopted is to ensure that the required carrier current cannot be present due to chopper action.

High frequency delta track circuit. The principal difficulty with existing styles of delta track circuit is that there is no frequency selectivity in the receiver stage. Thus broad band high frequency disturbances, associated with electric field coupling, could cause an 'early operation' when a train approaches the detection point. While this could be resolved by incorporating a band-pass filter in the delta circuits, uncertainty about the spectrum associated with this form of disturbance, suggested that suppression ar source was a preferable option. This has been achieved by connecting a relating large capacitance (4 μf) from the traction negative to the car-body. This reduces the high frequency disturbance to better than -20 dB, and is considered to be an adequate safeguard. The capacitor used is a far terminal device which also acts as the return conductor in the traction negative circuit. Failure of this component thus isolates the chopper equipment.

Definition of procedures for controlling disturbance current.

The principal concern is that under certain fault conditions the chopper equipment might operate at other than its designated frequency. While this is statistically unlikely, the possible wrong side failures which could occur are such that it is considered necessary to continuously check the chopper frequency in a fail-safe manner. This is undertaken on the prototype chopper train with a circuit developed by Westinghouse Signals, from an initial design concept by London Transport. This unit detects that the chopper equipment is either operating at its designated frequency or that it is not chopping. A novel feature of this detector is that the frequency is measured by coupling into the commutation circuit of the chopper.

In addition to defining the operating frequency of the chopper it is necessary to provide adequate input impedance, to limit substation generated harmonics, and adequate filtering of chopper generated harmonics. From a detailed study of worst case situations the test circuit shown in Fig.5 has been defined to specify the maximum level of chopper generated harmonics. To guarantee the same level of reliability in existing 125 Hz circuits the input impedance must be specified as being at least no worse than with existing rheostatically controlled trains. Since London Transport do not use relays which are transformer coupled through impedance bonds, there is no need to specify a higher input impedance for the same level of security, with broken rail conditions.

Generation of specification requirements.

Following experience to date the required standard of signal/traction interfacing would be met by chopper equipment which meets the following requirements :

- the chopper frequency is to be selected to avoid beating effects and generation of signalling frequencies;
- the chopper frequency must be fixed, although motor cut-out facilities must be considered as a normal requirement, if a multi-phase chopper is used;
- a fail-safe frequency detector must be incorporated in the chopper equipment to continuously monitor the operating frequency;
- the input filter must have a resonant frequency below 50 Hz ;
- the input filter components should be selected such that the worst case disturbance current is not greater than a value specified using the circuit shown in Fig.5.
- the input impedance of a 4-motor equipment should be not less than a value specified at 50 Hz, for any condition of chopper operation. It is a further requirement that the impedance at 50 Hz should not be capacitive.
- To avoid high frequency excitation due to electric field coupling an approved method of suppression at source is required. The method of capacitor suppression defined above is one example of such protection.

CONCLUSIONS

- In London Transport signalling circuits disturbance effects are principally due to mutual inductance coupling and electric capacitive coupling, from the earth isolated power supply rails.
- With existing 125 Hz systems mutual inductive coupling is the most significant form of disturbance. Due to the asymmetrical position of the traction positive rail, track-based and train-borne equipment will always be subject to some disturbance when either chopper-controlled or rheostatically controlled trains are operated.
- Since the calculation of mutual coupling is straightforward, then it is possible to control the magnitude of such disturbances in any given item of signal equipment, by controlling the magnitude of continuous harmonic currents and transient currents in the traction supply.
- From safety considerations it is essential that chopper equipment does not produce currents in the dc supply which are close to 125 Hz. This can be achieved by selecting a suitable value of fixed chopping frequency and using a fail-safe frequency monitor as a part of the traction equipment.
- From reliability considerations it is necessary to limit the total rms current induced in any given item of signal equipment. With chopper equipment this can be achieved by specifying the dimensions of the chopper input filter and associated input impedance.
- For the existing high frequency overlay track circuits it is possible that capacitive coupling could cause a change in the detection point. This effect will only be experienced with chopper equipment and can be controlled by 'suppression at source'.

- The work undertaken has confirmed that it is practicable to produce an interface specification which will permit compatible operation between new chopper equipments and the existing 125 Hz signalling system. The general principles described in this paper have been used to establish particular requirements for three new prototype chopper equipments, which are now being produced for the Central Line replacement stock.
- The effort which has been put into the investigation of signal interference effects has been justified, not only in terms of producing the necessary criteria for compatibility with existing 125 Hz systems, but also in providing the necessary background against which newer forms of jointless track circuit must be judged.

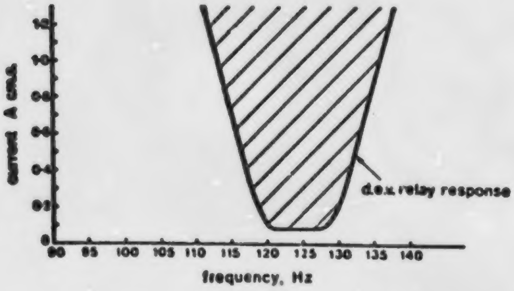


Fig.1

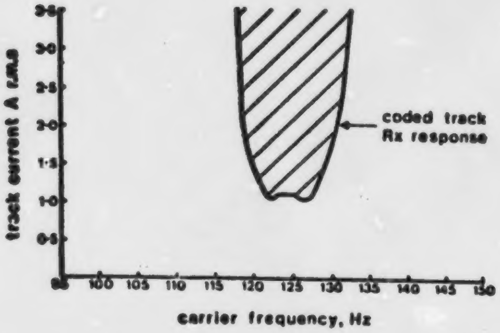


fig.2

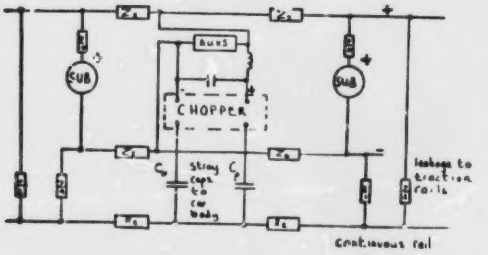
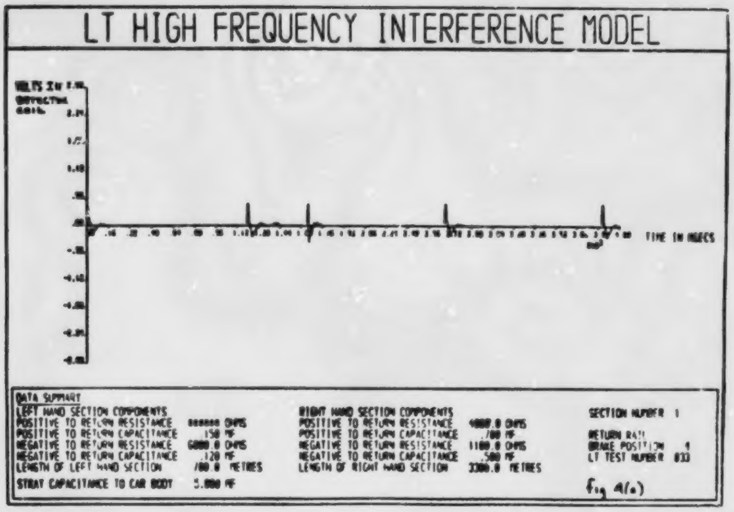


Fig 3

REFERENCES

1. Lowe,T.J. and Mellitt,B.
Thyristor chopper control and the introduction of harmonic currents into track circuits.
Proc.IEE, 121, 4, pp 269-275, (1974)
2. Duck,E.W., Lawrence,L.S., Lowe,T.J.
Thyristor chopper control and the introduction of harmonic currents into track circuits. Practical tests.
Proc.IEE, 123, 6, pp 523-530, (1976)
3. Hopkins,P.R.G.
Crosstalk between track circuits on adjacent roads of a railway system.
M.Phil.thesis, Brunel University, April'81
4. Frasco,L.A., Gagnon,R., Holmstrom,F.R.
Choppers affect operation of AF track circuits.
Rly.Gazette Int., 1980(4), pp 291-294.

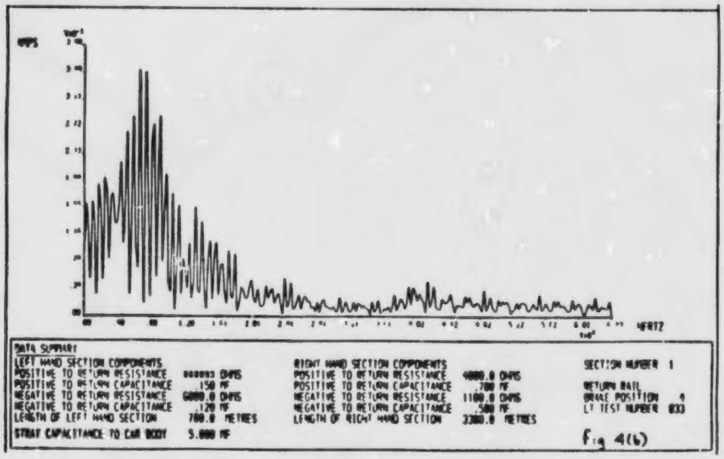


LT HIGH FREQUENCY INTERFERENCE MODEL

DATA SUMMARY

LEFT HAND SECTION COMPONENTS		RIGHT HAND SECTION COMPONENTS		SECTION NUMBER	1
POSITIVE TO RETURN RESISTANCE	****** OHMS	POSITIVE TO RETURN RESISTANCE	4000.0 OHMS		
POSITIVE TO RETURN CAPACITANCE	.150 MF	POSITIVE TO RETURN CAPACITANCE	.700 MF	RETURN RAIL	
NEGATIVE TO RETURN RESISTANCE	6000.0 OHMS	NEGATIVE TO RETURN RESISTANCE	1100.0 OHMS	BRAKE POSITION	4
NEGATIVE TO RETURN CAPACITANCE	.120 MF	NEGATIVE TO RETURN CAPACITANCE	.500 MF	LT TEST NUMBER	033
LENGTH OF LEFT HAND SECTION	700.0 METRES	LENGTH OF RIGHT HAND SECTION	3300.0 METRES		
STRAY CAPACITANCE TO CAR BODY	5.000 MF				

Fig 4(a)



DATA SUMMARY

LEFT HAND SECTION COMPONENTS		RIGHT HAND SECTION COMPONENTS		SECTION NUMBER	1
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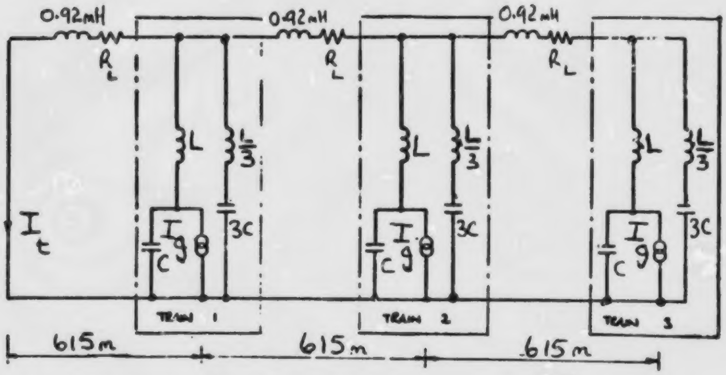
NEGATIVE TO RETURN CAPACITANCE	.120 MF	NEGATIVE TO RETURN CAPACITANCE	.500 MF	LT TEST NUMBER	033
LENGTH OF LEFT HAND SECTION	700.0 METRES	LENGTH OF RIGHT HAND SECTION	3300.0 METRES		
STRAY CAPACITANCE TO CAR BODY	5.000 MF				

Fig 4(b)



For R_L see data sheet 30

Fig 5

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EMC CONSIDERATIONS FOR ADVANCED PROPULSION DEPLOYMENT IN EXISTING U.S. TRANSIT ENVIRONMENTS

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USA

INTRODUCTION

Due to the potential advantages in operation, maintenance, and energy efficiency, solid-state power electronics is being increasingly utilized in the design of rail transit traction power and vehicle propulsion control equipment. In addition to new transit undertakings, established transit operators are anxious to take advantage of these potential benefits. However, based on past experience with early deployment of dc chopper technology in the U.S., one must proceed cautiously to guarantee compatiblity of these new technologies with existing installations. The purpose of this paper is to discuss potential electromagnetic compatibility (EMC) issues in introducing new solid-state propulsion technology (dc chopper and ac drives) onto existing installations for which they were not initially designed. Results of the paper draw heavily on our past experience and that of others.

BACKGROUND

In the recent past, there have been problems both in the U.S. and abroad in introducing solid-state dc chopper propulsion equipment on new and existing transit systems due to electromagnetic interference (EMI) between propulsion and signalling equipment (1,2,3,4).

Following an initial period of disruption, a cooperative effort between transit operator and supplier in the U.S. has led to acceptable solutions to these dc chopper EMC problems (5,6). The detailed nature of the problem and the resulting solution was dependent to some extent on the particular transit system's operation and equipment characteristics. The type of corrective action was also different for newly designed systems as opposed to older more established systems where changes in the existing installation are much more difficult and costly. In the latter case, except for minor changes in existing installation, any required design changes as well as the burden for compatibility necessarily was assigned to vehicle propulsion.

With the development of ac drives in the U.S. and abroad (Cf. A.C. and D.C. Advanced Propulsion Systems session this symposium), issues of EMC are once again a major concern of the transit operator and complicate his evaluation of potential benefits of ac drives versus dc choppers or more conventional switched resistor traction technology.

While foreign developments in this area are more advanced with extensive testing and a modest number of vehicles in revenue service (7,8,9,10), it has been difficult for the U.S. transit operator to derive the EMC consequences of ac drive installation in his environment from these developments.

APPLICABILITY OF PAST EMC EFFORTS

Both the approach and the measurement and analysis techniques developed to identify and resolve dc chopper EMC problems are directly applicable to ac drive EMC resolution (11). Equally important, the necessary human resources in terms of required expertise and a cooperative relationship among transit operators and subsystem suppliers have been demonstrated.

The WMATA EMC/EMI chopper test program is a good example of what must be done to support solid-state propulsion system deployment on an existing installation (12). Extensive laboratory testing of the propulsion system pre-production prototypes was conducted. Vehicle emissions data (conductive and inductive) was measured and tape recorded. Representative WMATA signalling equipment was configured in the laboratory for both worst case inductive and conductive susceptibility testing, vehicle emissions were injected, and interference margins established. An analysis was also conducted using vehicle emissions, susceptibility data, and coupling model.

Finally, a field test program using recorded vehicle conducted emissions injected into a portion of the acutal WMATA system was used to verify coupling of vehicle emissions from the traction power rail to the signalling system track circuits. At the same time, measurements were made to determine the empirical coupling coefficient and input rail impedance at signalling frequencies to verify the model. The details of this field test program are presented in an appendix at the end of the paper. These tests will be repeated at a later time utilizing the actual propulsion system installed on a vehicle at WMATA.

Based on this comprehensive test program, changes were recommended to assure compatibility with the existing installation. Recommended changes on the vehicle included a requirement for vital chopper frequency and line filter integrity checking. Only minor changes to the existing installation were recommended including a change-out of plug-in track circuit filters at certain locations to the manufacturer's narrow-band version. It was also recommended that WMATA consider interference-tolerant signalling equipment designs for future installations and extensions. Other related EMC experience in evaluating chopper deployment on existing installations is the work done at London Transport (13).

More specifically, as part of the ac drive development program in the U.S., inductive and conductive emissions measurements on prototype propulsion equipment have been performed using the techniques developed for dc choppers. Track circuit susceptibility test methods for audio-frequency track circuits have been supplemented to include tests for power frequency track circuits, these track circuits have been tested, and their susceptibility catalogued. Also, coupling models for conducted emissions have been developed for power frequencies. Tests have been developed and conducted to measure these model parameters. Finally, EMC analyses have been conducted based on these measurements.

WHAT REMAINS TO BE DONE

While some laboratory testing of propulsion and signalling equipment has been done, realistic conductive interference testing requires field measurements in a transit environment to both verify coupling model parameters and to exploit the actual conductive coupling mechanism by injecting ac propulsion conductive emissions into portions of the actual system. This is the best that can be accomplished until an ac propulsion equipped vehicle is available. This transition to property field testing is an important one in that it is the first real integrated test of initial laboratory testing and analysis.

FUTURE PREDICTIONS

What predictions can be made at this time regarding deployment of ac drives in existing environments in the U.S.? As a basis for assessing ac propulsion feasibility in this context while proceeding with development and testing, a technical report was prepared for US DOT early in their development program dealing with this issue for the NYCTA enviroment (14). This section will briefly expand on that preliminary analysis. Given the risk and the investment required to make a deployment decision, no definitive statement can be made until more field testing and verification of existing EMC data has been accomplished. Deployments outside the U.S. have been based on extensive property testing.

Compatibility of ac drives is dependent both on the specific implementation and configuration chosen as well as the characteristics of the existing transit installation. We shall concentrate only on issues of signalling system compatibility. Current ac drive designs include chopper/current source inverter, and PWM inverter with or without a front-end chopper; power semiconductor devices used include thyristors and GTOS (15). In the following, target transit installations will be divided into those using power frequency and audio frequency signalling equipment.

For the power frequency signalling installations (e.g. NYCTA), conductive emissions should be the dominant interference mechanism with no problems expected from undercar inductive emissions in this frequency range. Moreover, since in the past for dc choppers it was shown that the commutation process was the dominant source of inductive interference, those designs which do not require either commutation circuitry or a large commutation inductor should have very low inductive emissions. The primary method available for controlling conductive emission levels is the propulsion system line filter and its sizing. Therefore, compatible operation in this environment, once signalling susceptibility levels and coupling factors have been determined, would require proper sizing of line filter components with associated weight and size penalities. Dependent on the amount of security required, a vital power frequency monitor circuit and/or line filter integrity checking on board the vehicle - to cut-out propulsion if susceptibility level is exceeded - may be required. This in fact has been the experience on foreign properties (7,9).

For audio frequency signalling systems, the dominant interference mechanism should be inductive emissions. The major controlling factors are signalling frequency range, susceptibility level, and propulsion system design. For example, Helsinki metro which operates ac drives uses a signalling system design with frequencies chosen at the high end of the spectrum with high threshold levels comparable to power frequency track circuit levels (both these parameter values are approximately an order of magnitude larger than presently used in the U.S.). If inductive emission levels are too high for a given installation, reduction is not as straight forward as a line filter parameter change. As stated earlier, the dominant mechanism for inductive emissions has been the commutation circuitry. Level control in this case would require either component reconfiguration, shielding, or elimination of the commutation circuitry or inductive components by alternative design. Foreign experience in this area is limited since typically either different types of signalling systems are used or the minimum frequencies and thresholds chosen are an order of magnitude higher than in the U.S. Also, vital monitoring of audio frequencies onboard the vehicle as is done for power frequencies is complicated by the large number of signalling frequencies typically used in a given installation.

Frequency management cannot be used for EMC control for either the power frequency or audio frequency case because of the variable frequency requirements of ac drives. Therefore, for fixed installations, filtering at the signalling equipment does not help. Also, usually only minor changes in signalling equipment susceptibility threshold are possible without major modifications and the associated cost.

Given this prognosis and the nature of the uncertainties that exist, it should be clear that a careful evaluation of the characteristics of the specific installation as well as the vehicle can have a major impact on the risk and costs associated with ac propulsion system deployment in an existing transit environment.

REFERENCES

1. Frasco, L. A., Gagnon, R., and Holmstrom, F. R., April 1980, Railway Gazette International, "Choppers Affect Operation of AF Track Circuits."

2. Mellitt, B., November 1979, Railway Gazette International, "Signal Interference Effects with Chopper Controlled Traction."

3. Frasco, L. A., Gagnon, R., and Holmstrom, F. R., February 1980, Proceedings of the International Conference on Advanced Propulsion Systems for Urban Rail Vehicles, "Electromagnetic Compatibility of Advanced Propulsion Systems," Washington, D.C.

4. Amler, J., January 1978, Sponsored by Federal German Ministry for Research and Technology, "The Effects of the DC-Chopper Technology in Public Rapid Transit Passenger Transport (PRTPT)."

5. Hoelsher, J., and Rudich, R., November 1981, "Compatibility of Rate-Coded Audio-Frequency Track Circuits with Chopper Propulsion Drives in Transit Systems," IEE International Conference on 'Railways in the Electronic Age,' London, England.

6. Frasco, L. A., Holmstrom, F. R., November 1981, "EMC Consequences of Power Electronics Applied to Rail Transit", Proceedings of IEE International Conference on Railways in the Electronic Age, London, UK.

7. Griffe, P., March 1984, "Asynchronous Traction Experiments on the Paris Metro", Second International Symposium of Advanced Propulsion and Control for Urban Transit, Baltimore, Maryland.

8. Holma, H., March 1984, "Operational Experience of an AC Propulsion System in Revenue Service - The Helsinki Metro", Second International Symposium on Advanced Propulsion and Control for Urban Transit, Baltimore, Maryland.

9. Heider, H., and Dreimann, K., March 1984, "Operational Experience with AC Drives in the Federal Republic of Germany", Second International Symposium on Advanced Propulsion and Control for Urban Transit, Baltimore, Maryland.

10. Yamanaka, T., March 1984, "VVVF Inverter Control System For Electric Cars", Second International Symposium on Advanced Propulsion and Control for Urban Transit, Baltimore, Maryland.

11. UMTA/TSC, July 1980, "Draft Recommended Practice Rail Transit Intra-System Electromagnetic Compatibility Vehicular Electrical Power and Track Circuit Signalling Subsystems."

12. Krempasky, J. F. (WMATA), Frasco, L. A. (Frasco & Associates), and Clark, G. E. (Gibbs & Hill), June 1982, "EMI/EMC Rail Testing Program at WMATA", APTA Rail Conference, Cleveland Ohio.

13. Hopkins, P. G. G., and Mellitt, B., March 1984, "London Transport Experience with Chopper Interference", Second International Symposium on Advanced Propulsion and Control for Urban Transit, Baltimore, Maryland.

14. Frasco, L. A., August 1981, "EMC Impact of AC Propulsion System Deployment at the NYCTA", Frasco & Associates Technical Report, prepared for U.S. Department of Transportation.

15. Matsuda, H., and Takeuchi, M., March 1984, "Power Semiconductor Devices For Transit Applications," Second International Symposium on Advanced Propulsion and Control for Urban Transit, Baltimore, Maryland.

APPENDIX

WMATA TAPE RECORDED CONDUCTED EMI TEST

INTRODUCTION

On November 10-12, 1981, as part of the WMATA EMI/EMC Chopper Rail Car Testing Program, conductive interference tests were performed in the vicinity of Van Ness station on the Red Line. These tests used tape recorded vehicle conducted emissions. The tape recordings had been generated earlier at the Westinghouse 2L laboratory in Pittsburgh using the WMATA engineering prototype chopper propulsion system being tested there. Using an instrumentation tape recorder and power amplifiers, these interference signals were injected at precisely controllable levels directly onto an unpowered third rail of the WMATA system near Van Ness. This procedure allowed the simulation of the electromagnetic environment (i.e. conducted EMI) that would exist with the actual chopper propelled vehicle operating on the system. By using an amplifier to increase the recorded emission levels, effects of multiple-car trains were simulated.

The major accomplishments of the test were the following:

1. Verified test procedure by correlating field test results with data collected earlier at Westinghouse 2L laboratory.
2. Used test procedure to simulate single and multi-car train (i.e. up to 8 cars) and observed effects on WMATA subsystems (including signalling, radio communication, telephones, DTS, etc.) For the levels of conducted EMI simulated no significant system interference was observed due to conducted EMI.
3. Determined empirically the conductive emission coupling coefficient, i.e. fraction of conductive third rail emission current which couples and circulates in track circuits. This value was found to be significantly less than the theoretical worst case bound derived earlier. Values of approximately 0.10 or less were measured as opposed to earlier theoretical predictions of 0.17.
4. Using the same test set-up, verified the impedance per unit length of third rail/running rail combination. Agrees with theory and earlier measurements by others (i.e. approximately 1 uh/m of inductance). Values for this parameter and coupling coefficient are necessary for conductive susceptibility analysis.

Based on the results of this testing campaign, this method of testing using prerecorded conducted interference signals played back through an actual operating system at adjustable and controllable levels, appears to be an easy and effective method for measuring and observing potential interference characteristics of actual chopper rail car operation. The following sections will briefly summarize details of the test including test set-up and results.

TEST CONFIGURATION

Figure 1 shows the general test configuration. It was used throughout the testing with slight variation. The current source I_s represents the recorder amplifier instrumentation. This current source was also placed near location D to simulate coupling effects for short track circuits. The impedance bond at location D was disconnected from the running rails during the simulated long track circuit test (hence the dotted representation). The bond at location E does not affect the test set-up due to the short circuit at F. Circuit parameters at the bond location AB (a 2320 Hz bond) were measured (e.g. I_1, I_2, I_3, V_B). Currents were sensed using a standard current probe. The impedance seen by the interference current source I_s (i.e. third rail/running rail impedance per unit length) was measured using a dual input digital network/spectrum analyzer. To verify/correlate test procedure with tests and data collected at Westinghouse 2L laboratory, a 100% imbalance test was configured to directly feed interference signals into impedance bond at location AB. To accomplish this the impedance bond was disconnected from the running rail at point A and third rail connection point C moved to this bond terminal. This simple change created a single path between current source I_s and the bond through the third rail and one of the running rails.

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SUMMARY OF TEST RESULTS

A. Verification of Test Procedure

Using the configuration described above to simulate 100% imbalance, conductive interference current I_S was increased (i.e. amplified) until the track relay picked for the track circuit receiver associated with the impedance bond at location AB. A gain G = 11.7db or factor of 3.84 was required to accomplish this. Using a separate standard CW measurement procedure to establish the specific operating threshold of the track circuit it was determined that it was set approximately 3 times the mininum threshold - the threshold used for Westinghouse 2L lab testing. Normalizing the gain G by this factor yields a $\hat{G} = 3.84/3 = 1.28$. This result is in close agreement with 2L lab results of 1.25 (cf. Westinghouse Engineering Report #863).

B. Simulation of Single/Multiple Car Train

Using the configuration of Figure 1, the pre-recorded single car conducted emission signal was amplified by 18.2db or a factor of 8.13. This factor represents a worst case upper bound for an 8 car train (i.e. it neglects beneficial effects of substation, rail, and vehicle impedances). Using this configuration, recordings of vehicle operation in propulsion, braking, and pulse-skipping modes were driven into the WMATA system. For these levels of simulated conducted EMI, no significant system interference was observed in signalling or other major WMATA subsystems (i.e. radio communication telephones, DTS, etc.). Quantitative levels of this simulated interference were difficult to measure even at the output of track circuit receiver filters. As will be seen in section C on coupling coefficient, the different results of tests A and B are consistent and can be quantitatively justified based on the actual coupling factor observed.

C. Determination of Conductive Emission Coupling

Using the test configuration shown in Figure 1 with I_S a CW current source, circuit parameters were measured to allow the calculation of conductive emission coupling coefficient; i.e. the fraction of conductive third rail emission current which couples and circulates in a track circuit loop (I_C in Figure 1). These parameters were measured for a short (128') and a long (728') track circuit configuration. I_C was calculated in two ways from measured data:

$$1)\quad I_c = \frac{|I_1 - I_2|}{2}\ ;\quad 2)\quad I_c = \frac{V_B}{Z_B}$$

where Z_B is bond input impedance. Z_B for this bond was directly measured in place. The results Z_B = .29 (@2320Hz) agrees with result as measured by the author at the Westinghouse 2L lab as well as with GRS test data. Table I summarizes results of this test series.

Typically measurements made for short length track circuits yield smaller values of coupling coefficient. This is due to the effect of bond impedance Z_B; i.e. for short track circuits it represents a significant portion of the track circuit loop impedance. As track circuit length increases this effect becomes negligible. To demonstrate this Z_B effect in the short track circuit case the measurement frequency was moved off bond resonance to 2969Hz where Z_B has a much lower value. As expected the coupling coefficient increases. Finally, measurements were taken using a long track circuit (728') and I_S at a high current level to minimize effect of noise and spurious signals.

Therefore, based on these test results, a bound on conductive coupling coefficient independent of track circuit length of approximately 0.10 (10%) has been calculated from measured data. This value is significantly less than the previously used theoretical worst case bound of 0.17. Present conjecture as to this difference between theory and experiment include ideal geometry assumptions in the theoretical analysis, influence of surrounding structure (i.e. concrete, etc.) on fields, and possible autotransformer effects of the impedance bond.

D. Measurement of Third Rail/Running Rail Impedance

Taking advantage of the test configuration of Figure 1, the input impedance Z_i seen by the interference current source I_S (i.e. third rail/running rail impedance per unit length) was measured using a dual input digital network/spectrum analyzer. Measured values of $Z_i = 0.645\,\Omega \angle 63°$ at 2320 Hz and $Z_i = 1.06\,\Omega \angle 70°$ at 4 KHz. The short track circuit was used for these measurements with 35 meters of third/rail running rail. These results are consistent with theory and earlier measurements of others (i.e. approx. 1 uh/m of inductive component).

FIGURE 1

CONDUCTED TEST CONFIGURATION

AT VAN NESS STATION

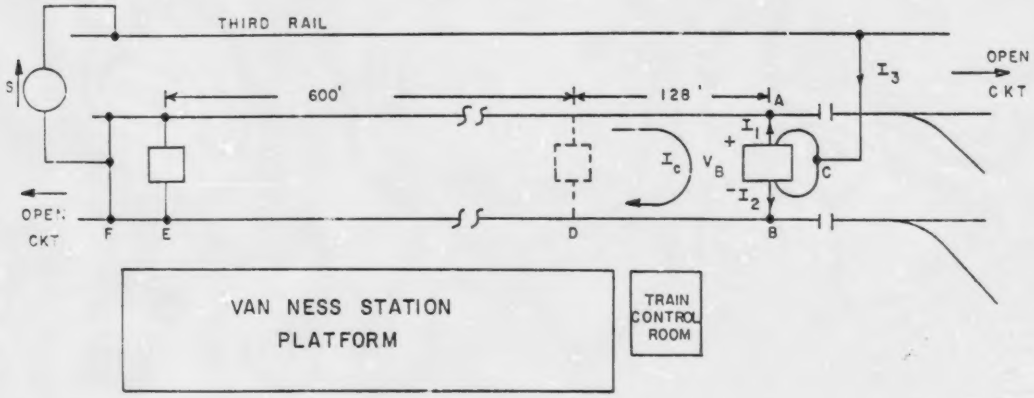
THIRD RAIL
S
600'
128'
A
I_3
OPEN
CKT
I_1
+
I_c
V_B
$-I_2$
C
OPEN
CKT
F
E
D
B
VAN NESS STATION
PLATFORM
TRAIN
CONTROL
ROOM

TABLE I

CONDUCTIVE COUPLING COEFFICIENT

MEASUREMENT RESULTS

TRK CKT LENGTH	I_S (MA)	I_1 (MA)	I_2 (MA)	V_B (MV)	I_C (MA)	MEAS FREQ (HZ)	I_C/I_S
128'	48.4	21.8	26	—	3.65	2320	.075(7.5%)
128'	48.4	—	—	1.1	3.79	2320	.079(7.9%)
128'	822.2	350.8	467.7	—	58.45	2320	.072(7.2%)
128'	861	335	519	—	92	2960	.107(10.7%)
728'	3.89a	1.57a	2.32a	—	.375a	2320	.096(9.6%)

THE REALITY OF CHOPPER GENERATED DISTURBANCES IN POWER FREQUENCY SIGNALS

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SUMMARY

This paper describes theoretical and practical work, undertaken during the last decade at the University of Birmingham and on several d.c. supplied railways, concerned with the effects of traction generated disturbances in low frequency track circuits and train control systems. Following a description of the characteristics of such systems, the nature of disturbance mechanisms are briefly summarised with respect to chopper generated and traction supply generated harmonic components.

While the concern of signal engineers in this area can be clearly appreciated it is evident that many of their initial fears were due to a lack of knowledge of the harmonic spectrum associated with the traction return current, for chopper-controlled and rheostatically controlled cars. In power frequency supplied signalling systems the principal source of potentially dangerous failures is associated with substation generated ripple at 50 or 60 Hz, providing sensible design features are incorporated in the chopper equipment.

It is concluded that the nature of conductive and inductive disturbances are now well understood and for any given application it should be possible to design mutually compatible equipment.

INTRODUCTION

The development of power electronic equipment has significantly altered the nature of traction control equipment used for rapid transit systems. Chopper equipment is now used extensively and the use of inverter-fed induction motor drives is being advocated[1] by some organisations. Developments in GTO technology[2] should simplify power electronic circuit configurations and further improve equipment performance. Despite the many benefits which are consequent upon the use of power electronics in traction, some concern about possible adverse effects on signalling systems have been expressed over the last decade[3]. Since power electronic equipment may produce harmonic components in the traction return current which are within the operating bandwidth of track based signalling systems, the possibility of disturbance is present and the concern of the signal engineer can be clearly appreciated.

When considering interference/disturbance effects in signal circuits it is useful to distinguish between the older type of low frequency carrier systems, which typically operate below 125 Hz, and the more recently developed audio frequency (af) systems which operate typically in the range from 1 to 10 kHz. Track circuits, which operate on carrier level and phase detection, have been used extensively in d.c. supplied railways. In particular 50 Hz and 60 Hz track circuits which use a Ferraris disc vane-relay[4], are used in double and single rail form on many existing and recently developed transit systems[5]. Possible advantages associated with af carrier systems include the use of coding to improve security, a reduction in size of equipment, the elimination of large impedance bonds and the use of non-jointed track. It should be noted that not all existing af systems necessarily provide these features.

While af systems may or may not incorporate sophisticated coding features for security, they invariably operate at power levels which are typically one order of magnitude below that associated with low frequency systems. Due to this relatively low power level, 'wrong-side' failures have been reported in simple af track circuits in the USA. With coded af systems the possibility of 'right-side' failure is also greater due to the lower power levels involved. While right-side failures are intrinsically safe, frequent failures would not be acceptable from operational considerations.

This paper is concerned specifically with disturbances in low frequency track circuits and refers to practical and theoretical work undertaken since 1972. With such systems the principal disturbance mechanism is associated with conducted interference[7] in the traction return circuit, although inductive effects from adjacent power supply conductors have also given rise to some problems[8].

CHARACTERISTICS OF LOW FREQUENCY SIGNALLING EQUIPMENT

In many railways double element vane relays are used for train detection with a carrier frequency of 50 or 60 Hz. In such circumstances the provision of signalling power supplies is straightforward since the local industrial frequency supply may be used. Some authorities, conscious of possible disturbance effects due to industrial frequency interference, have adopted other carrier frequencies which necessitate special power supply arrangements for the signalling system. Examples of such carriers include 25 Hz, 33.1/3 Hz, 75 Hz, 83.1/3 Hz and 125 Hz.[9]

The double element vane relay (DEV) is essentially a two-phase induction motor which will only produce a non-zero average torque when both windings are energised with currents at the same frequency and with an appropriate phase displacement. For continuous energisation both the auxiliary and track fed coils must be energised from the same frequency source with some mutual phase shift between the currents in the coils. In practice this mutual phase shift may be provided by capacitors or by the use of suitable inductive - resistive networks. The phase shift feature can be used to provide an indication of block joint failure by arranging for the auxiliary coils in adjacent track circuits to be phase revered.

DEV relays are used in single and double rail track circuits. In double rail circuits it is normal practice to use transformer coupling at both ends of the track circuit, to increase the carrier frequency current in the running rails with respect to the operating current required in the track fed coil. In such circuits the transformer may form a part of the impedance bond or may be a separate transformer. Tuning circuits at the carrier frequency are sometimes used to improve coupling into the track and relay circuits. In single rail track circuits the relay may be connected directly across the track or coupled via a transformer depending on the length of the track circuit and the specified train shunt.

Most modern metro systems use cab-signalling to provide speed commands, based upon an overlay circuit in the occupied block section. A commonly used arrangement[10] involves pulsing the track circuit carrier at relatively low frequency, typically in the range 1 to 3 Hz, although a more recent system which uses 50 Hz track circuits has overlay circuits which operate in the audio frequency band.[5] With either arrangement train-borne antenna are used to detect the magnetic fields set up by the coded carrier. The speed commands are decoded by train-borne equipment which uses carrier frequency and code rate filters of appropriate bandwidth.

Consequences of traction generated disturbances.

When narrow band signalling systems are subjected to disturbances from the traction equipment there are three possible consequences:

(1) no perceived effects since the magnitude on in-band disturbances are less than threshold values,

(2) a normally energised circuit is de-energised by the in-band disturbance which over-rides the normal signal,

(3) a normally de-energised circuit is energised by the in-band disturbance, which acts as an alternative to the normal signal

Since low frequency signalling systems are routinely designed to be fail-safe, consequence (2) defines a right-side failure, which is operationally inconvenient, which consequence (3) defines a wrong-side failure which is potentially dangerous since it can correspond to false clearance of an occupied block section or the issuing of an incorrect speed command.

Sources of disturbance

The disturbances which can exist in signal circuits are generally due to time varying currents and voltages which exist in power circuits and include :

- the traction positive conductor system,
- the running rails which form the traction return,
- adjacent ac power conductors used for railway purposes,
- adjacent ac power conductors used for other purposes,
- train-borne inductive sources,
- train-borne capacitive sources.

COUPLING MECHANISMS

Forms of coupling

The disturbances which can exist in signal circuits can be classified in terms of :

- electric coupling
- inductive coupling
- conductive coupling

Electric coupling

This refers to capacitive coupling between circuits and is manifested by charging and discharging currents which appear in the disturbed circuit. Experience to date suggests that this form of coupling is only significant in railways which use earth-insulated positive and negative traction supply conductors, such as London Transport and some more recent LRT systems.

Inductive coupling

This refers to mutual coupling and, in the railway context, there are three particular cases of interest :

- coupling between parallel isolated circuits
- direct inductive coupling from train-borne equipment,
- coupling between parallel circuits with a common earth return.

Coupling between parallel isolated circuits can be defined in terms of the per-unit length mutual inductance between a signal circuit which has conductors a,b and a power circuit with conductors 1,2 . In this case :

$$m_{ab,12} = \frac{\mu_o}{2\pi} \log \exp \left[\frac{d_{1a}\ d_{2b}}{d_{1b}\ d_{2a}} \right] \text{ H/m}$$

This form of coupling is of particular interest when de-energised industrial frequency track circuits are subject to pick up by induction from adjacent power supply conductors. The single phase case defined above can be extended for a balanced three phase set to give :-

$$m_{ab,123} = \frac{\mu_o}{2\pi} \left\{ \log \exp \left[\frac{d_{1a}}{d_{1b}} \left(\frac{d_{2b}\ d_{3b}}{d_{2a}\ d_{3a}} \right)^{1/2} \right] \right.$$

$$\left. + j \log \exp \left[\left(\frac{d_{2a}\ d_{3b}}{d_{2b}\ d_{3a}} \right)^{\sqrt{3}/2} \right] \right\} \text{ H/m}$$

Direct inductive coupling between train-borne components and track based circuits is of particular significance in chopper-controlled and inverter-controlled traction equipments, where the magnetic fields associated with armature circuit and commutation chokes have caused difficulties in some af track circuits[6]. This particular effect was observed during tests on a 125 Hz track circuit at a London Transport test site in 1974. This 'close-up' effect, due to direct coupling from the undercar components, was not significant in the circuit being tested. This early conclusion has been confirmed by later measurements in two systems which use 50 Hz track circuits and one which uses 83.3 Hz track circuits. While direct inductive coupling is of particular importance in low power af systems, it has not proved to be of any significance to date, in the higher powered low frequency systems.

Coupling between parallel circuits with earth return is of particular interest in calculating psophometric noise in railway telephone circuits and longitudinal induced voltages, which can be hazardous to railway staff under fault conditions. For this case the per-unit mutual inductance can be calculated using the approximate form of Pollaczechs equation[11]. This form of disturbance is not particularly significant in power frequency track circuits, in railways which use earth return.

Conductive coupling

This refers to coupling between two circuits which share a common impedance. In the railway context this usually refers to the condition where the signal circuit and the traction return circuit both use the same running rails. The voltage generated across the common impedance by the traction return current will act as a 'disturbance source' in the signal circuit, producing a disturbance current which is proportional to the per-unit-length impedance of the power circuit conductors. In strictly academic terms there will also be a mutual coupling effect, but the relative values of the effects are such that in power frequency track circuits it is the impedance coupling which is important. This is the most significant source of coupling into track circuits when the running rails are used for both train detection and traction return current.

SOURCES OF DISTURBANCE IN THE TRACTION RETURN

Chopper generated harmonics in the traction supply

The use of chopper control equipment introduces ac current, at harmonics of the fundamental chopping frequency, into the traction supply. In practice the magnitude of harmonic current appearing in the dc supply is made small by the use of a low pass input filter, normally consisting of a simple LC circuit. When a u phase chopper is connected to such a filter, controlling a total dc current of I_t at a fundamental chopping frequency of f_c, then the greatest magnitude of the $(n\,u\,f_c)$th harmonic is given by :

$$I_\ell(n\,u\,f_c) = \frac{\sqrt{2}\,.\,I_t}{n\,u\,\pi}\,.\left(\frac{f_o}{n\,u\,f_c}\right)^2$$

In this equation f_o is the resonant frequency of the input filter and n = 1,2,3 etc. This equation assumes that the u choppers are identical and that dc motor current ripple is negligible. This implies that only harmonic components at integer multiples of $(u\,f_c)$ will exist due to chopper action. In practice, due to chopper circuit unbalance, smaller components at multiples of f_c will also be present. The above equation is valid so long as the basic chopper frequency is at least 5 times greater than the resonant frequency of the filter. As the mark-period ratio of the chopper changes the magnitude of chopper-generated components will change and the values given by the above equation refer to the maximum value only.

The magnitude of the chopper generated components are also clearly dependent on the resonant frequency of the filter. In practice the source inductance of the traction supply, which is typically 1.5 mH/km, will reduce the natural frequency of the filter and increase the attenuation of the chopper generated components. In terms of magnitude only, the worst case thus corresponds to a train being just adjacent to a substation feedpoint.

Substation generated power frequency harmonics.

Since the dc traction supply is obtained by polyphase rectification small ripple voltage components will be present in the output voltage spectrum. An estimate of the value of such components can be estimated by using the equation for the no-load voltage rms component :-

$$V(n\,p\,f_s) = \sqrt{2}\,V_{dc} / (4n^2\,p^2 - 1)$$

This equation implies that for a p pulse converter only integer multiples of $(n\,p\,f_s)$, with n = 1,2,3 etc, will appear in the output. Since 6 or 12 pulse rectifiers are used in practice this implies that only multiples of 300 or 360 Hz will exist. In fact this condition is only satisfied if the rectifier circuit is perfectly balanced. In practice such balance rarely exists and the measured output voltage spectrum usually contains smaller components at other multiples of mains frequency. Even harmonics of the power supply frequency are regularly observed due to differences in magnitude between the three phase voltages.

The resulting current flow at mains harmonics is determined by the input impedance of the traction equipment. For most mains frequencies the capacitor of the input filter is virtually short-circuited and the input impedance is effectively that of the supply conductors in series with the input choke. For the fundamental component of 50 or 60 Hz this assumption is not reliable and the effect of filter capacitance must be included.

Practical measurements of ripple current and voltage

Several sets of measurements have been made of voltage and current harmonics on four different railways, with 650V and 1500V dc supplies, in association with chopper interference measurement programmes. From these measurements the following general comments are deduced :

Chopper generated harmonic current. Practical tests confirm that the apparent fundamental chopping component can be predicted using the equation presented above. When a two-phase chopper is used then the return current spectrum will usually contain components at the actual chopping frequency, typically at 20% of the amplitude expected from a single phase chopper of the same rating. In practice the full magnitude of the chopper harmonics will only be seen at positions which are close to the train or the substation feed, due to the tendency of ac current to enter earth circuits.

Substation generated ripple voltage. While the no-load balanced equation presented above provides a useful guide, many non-integer pulse number harmonics are presented in practice. This is illustrated in table 1, which lists the range of measured selected harmonics on 12 pulse silicon diode equipment which provides a 650V supply. For railways which use power frequency track circuits, the magnitude of the 50 Hz or 60 Hz component is of particular interest. With normal rectifier connections the equivalent voltage source at the fundamental frequency is small. However, in the unlikely event of a broken arm failure in a 6 pulse rectifier, the fundamental frequency component can become very large. This is illustrated in table 2, which contains data obtained on a 1500V dc supplied system with various rectifier configurations set up for test purposes. The broken arm results confirmed an earlier decision to detect for 50 Hz voltage ripple, above a certain threshold, at every dc substation.

Chopper frequency and mains harmonics due to several trains.

When a single train operates in a single end fed section it is a straightforward matter to calculate the harmonic currents in the traction return, using the ideas defined above. When more than one train is to be considered then simple algebraic models become cumbersome and computer based numerical solutions are more convenient. Since the ac source impedance of the traction supply is of the same order as the input impedance of the chopper cars, the loading effect of trains cannot be ignored. To illustrate this point predicted values of worst case chopper generated and mains generated components for several trains are given in table 3. In undertaking these calculations it was assumed that all chopper equipment operates synchronously and at the value of mark-period ratio to give the peak chopper generated components simultaneously.

When considering the situation with several trains operating between substations the following points should be considered :-

(a) for chopper generated harmonics the peak interference current in a track circuit will correspond to the maximum number of trains in section, with all choppers operating mutually in phase, working into a single end fed section. The track circuit subject to peak interference will be that which is adjacent to the track circuit.

(b) the peak interference currents due to chopping action as predicted by (a) are unlikely to occur in practice and the values obtained should be regarded as absolute worst case,

(c) for power supply generated harmonics the peak interference in a track circuit will correspond to the maximum number of trains in section,

(d) the peak interference currents due to power supply harmonics predicted by (c) will occur in practice, since it is likely that all trains in section will operate above base speed simultaneously.

Transient currents due to filter charging

The use of chopper equipment introduces low frequency transient responses associated with the characteristic frequency of the filter, when there is a step change of traction voltage. At first sight it would seem sufficient to ensure that the resonant frequency of the filter should be less than the operating frequency of the track circuit. However it has been demonstrated that a dev relay will transiently respond to the third, fifth or seventh harmonic of the transient inrush current. How important is this effect ? Providing that the track relay is followed by a slow to pick relay, as is common practice to deal with transients in general, then this effect is not significant. Even if the track relay is not followed by such a delay, then transient pick up of the relay in an occupied section is only significant if latched circuits are involved. In any particular railway situation this effect can be assessed and appropriate design measures adopted.

DISTURBANCES IN TRACK CIRCUITS

Need for in-band components for wrong-side failure.

The principal concern with traction generated interference in low frequency track circuits, is that a disturbance voltage will cause a de-energized track relay to be picked up while a train is in the block section. For this to occur an 'in-band' component of appropriate magnitude must be contained in the traction return current. In principle the in-band component could be generated by inter-modulation products, but this would require non-linear detection. Clearly providing that the chopper operating frequency can be guaranteed to be greater than the operating frequency of the track circuit, then harmonic chopper generated interference could never cause pick-up providing the input circuit is linear. In practice with 50 Hz or 60 Hz track circuits, the possibility of maloperation due to inductive[8] or conductive coupling from fundamental power frequency components is more of a possibility, since failure conditions can be identified which would produce 50 or 60 Hz components in the traction return.

Single rail track circuits

Single rail track circuits are used at points and crossings and also on approach roads. With this type of circuit most of the traction return current will flow through the continuous rail and, in an occupied track circuit, the relay will see the volt drop produced by return current. Practical measurements have confirmed that a worst case value of about 1.25 μH/m can be used to undertake disturbance current calculations in this case. Since single rail circuits are often used in points and crossings, the effective impedance of the circuit should include any long loops of connecting cable. At higher frequencies the increasing ac resistance of the rails should be accounted for in such calculations[12].

Double rail track circuits

Providing that the harmonic return current is divided equally between the two running rails then there will be no disturbance in a relay which is connected across the impedance bond.

With an overhead supply system, double rail track circuits are usually balanced and disturbance effects will only be evident under earth fault or bond saturation conditions. In practice it is relatively straightforward to investigate any of these effects by defining the track circuit and associated faults by a circuit theory model. It is convenient to undertake such calculations using a computer, since the magnetic coupling between the two halves of the primary winding and the secondary produces relatively complex equations.

With a third rail supply system there is a natural unbalance in the traction return current, due to the asymmetrical magnetic field pattern caused by the side rail conductor. The degree of unbalance depends upon the frequency, the relative permeability of the rail steel and, by implication, the flux density within the return rails, as well as the geometrical disposition of the traction positive with respect to the two running rails. In practice the natural unbalance is countered to some extent when magnetically coupled impedance bonds are used. It is clear that this is a complex situation best resolved by practical measurements. Practical unbalance of 30% has been reported in low frequency track circuits.

Practical measurements on double rail circuit. Several practical tests have been conducted on 50 Hz relays in 1500V and 650V systems. The general outcome of these tests is that the 50 Hz current due to substation ripple is very low, compared with normal operating levels, unless the broken arm rectifier condition occurs. A set of typical results for current in a de-energised track circuit, for a variety of operating conditions with chopper cars and rheostatic cars, for balanced, unbalanced and disconnected half-bond conditions produced a range of average 50 Hz disturbance current from 0.3 to 20 mA, in a relay with a minimum pick up current of 140 mA. During these tests this pick up level was only exceeded transiently for periods less than 50 ms.

Measurements of direct coupling close-up effects has produced similar results, while the chopper frequency components can be clearly seen, the 50 Hz value observed for about 200A dc in the 250 Hz chopper did not exceed 1 mA. This is illustrated in table 4.

MAKING MEASUREMENTS AND PROCESSING RESULTS

Instrumentation and technique

The measurement of harmonic current in the traction return current has been undertaken using ferrite toroids with an inner diameter of 100 mm and a guaranteed permeability of 15 ± 0.5, for a change of dc current from 0 to 1000A. By locating these toroids around bond cables it is relatively straightforward to deduce the ripple current harmonic spectrum by suitable post-processing of the tape recorded signals. In situations where a cable disconnection is not feasible, such as in a traction substation, an air cored toroid upon a flexible former, has been used satisfactorily. The obvious advantage of this arrangement is that the induced voltage is not dependent on the position of the coil, providing whole turns are used to encompass the power conductor.

Computer based data analysis

While it may be convenient to assess the harmonic spectrum as a test proceeds, the time limits imposed by railway possessions favour a well organised schedule for obtaining results, followed by a more relaxed assessment of the recordings when the possession is surrendered. To this end a computer based analyser has been developed using a CED analogue data acquisition unit controlled by a 16 bit microcomputer at the University of Birmingham. Providing a pick-up truck is available then this equipment is 'portable' and it has been used to produce many 'software' pictures using an associated plotter. A typical output is shown in fig.1.

CONCLUSIONS

The sources of interference current associated with power electronic equipment are well understood and in any new railway application it should be possible to design compatible signalling and traction control systems.

For low frequency systems which use dc relays it is sufficient to ensure that the chopper equipment does not generate harmonics at the in-band signalling carrier frequencies. This can be guaranteed by monitoring the operating frequency of the chopper unit with respect to its anticipated frequency schedule.

It is desirable that the resonant frequency associated with the chopper input filter should be less than the signalling carrier frequency. In practice this is not a difficulty with systems which use carrier frequencies greater than 50 Hz. Even if the track relays are transiently energised for short periods, the use of sensibly set follower time delay relays will overcome this problem.

With signalling systems which use 50 Hz or 60 Hz carriers the possibility of wrong-side operation due to industrial frequency disturbance, by induction or by conductive coupling from substation ripple, is more likely than that due to properly specified chopper equipment.

References

1. Albert,H.,Reichel,W.
Three phase a.c. propulsion system at Hamburg Hochbahn AG.
Proc.Int.Conf.Advanced Propulsion Systems for Urban Rail Systems, 1980, pp 119 - 132.

2. Kanzaki,T.,Yanagida,K.,Yasuoka,I.
Inverter control system for driving induction motors in rapid transit cars using high power GTOs.
IEEE Trans. IGA, 1982, pp 145 - 155.

3. Lowe,T.J.,Mellitt,B.
Thyristor chopper control and the introduction of harmonic current into track circuits.
Proc.IEE, 1974, 121(4), pp 269 - 275.

4. Shipp,D.G.
Track circuits in dc electrified areas.
Proc.IRSE, 1952, pp 108 - 134.

5. Thornber,D.
Signalling and train control of the Hong Kong Mass Transit Railway.
Hong Kong Engineer, Jan.1982, pp 31 - 37.

6. Frasco,L.A.,Gagnon.R.,Holmstrom,F.R.
Choppers affect operation of A.F. track circuits.
Rly.Gazette Int.,1980(4), pp 291 - 294.

7. Mellitt,B.
Signal interference effects with chopper controlled traction.
Rly.Gazette Int., 1979 (11), pp 999 - 1003.

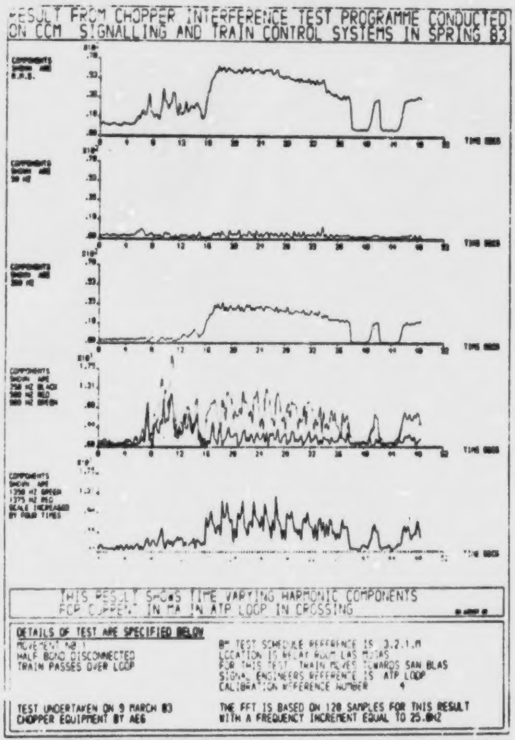
8. Manders,A.H.E.,Hofkens,G.A.,Shoenmakers,H.
Inductive interference of the signal and protection systems of the Netherlands Railway by overhead lines running parallel with the railway.
Conference Proc. CIGRE, 25th Session, Bulletin 1, 1974, 36(02), Part 1, pp 1 - 14.

9. Duck,E.W.,Lawrence,L.S.,Lowe,T.J.
Thyristor chopper control and the introduction of harmonic current into track circuits - practical aspects.
Proc.IEE.,1976, 123(6), pp 523 - 530

10. Taylor,S.F.,et al.
Evaluation of signal/control system equipment and technology.
F.R.A.,Washington,
Dec.1978, PB - 296 494

11. Klewe,H.R.
Interference between power systems and telecommunication lines.
Edward Arnold, ERA, 1958

12. Mellitt,B.
Data transmission characteristics of railway tracks.
Electronics Letters, 1973, 9(23), pp 550 - 1.



RESULT FROM CHOPPER INTERFERENCE TEST PROGRAMME CONDUCTED
ON CCM SIGNALLING AND TRAIN CONTROL SYSTEMS IN SPRING 83

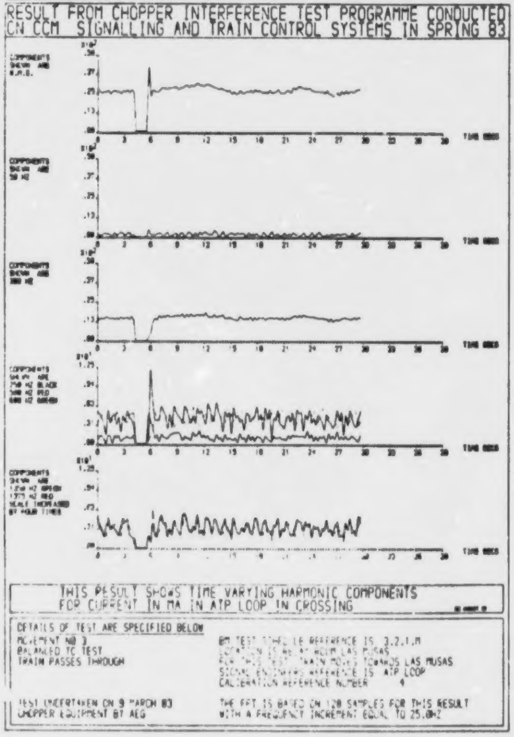
THIS RESULT SHOWS TIME VARYING HARMONIC COMPONENTS
FOR CURRENT IN MA IN ATP LOOP IN CROSSING

DETAILS OF TEST ARE SPECIFIED BELOW
MOVEMENT NO 1
HALF BOND DISCONNECTED
TRAIN PASSES OVER LOOP

BR TEST SCHEDULE REFERENCE IS 3.2.1.M
LOCATION IS RELAY ROOM LAS MUSAS
FOR THIS TEST TRAIN MOVES TOWARDS SAN BLAS
SIGNAL ENGINEERS REFERENCE IS ATP LOOP
CALIBRATION REFERENCE NUMBER 4

TEST UNDERTAKEN ON 9 MARCH 83
CHOPPER EQUIPMENT BY AEG

THE FFT IS BASED ON 128 SAMPLES FOR THIS RESULT
WITH A FREQUENCY INCREMENT EQUAL TO 25.0HZ



RESULT FROM CHOPPER INTERFERENCE TEST PROGRAMME CONDUCTED
ON CCM SIGNALLING AND TRAIN CONTROL SYSTEMS IN SPRING 83

THIS RESULT SHOWS TIME VARYING HARMONIC COMPONENTS
FOR CURRENT IN MA IN ATP LOOP IN CROSSING

DETAILS OF TEST ARE SPECIFIED BELOW
MOVEMENT NO 3
BALANCED TC TEST
TRAIN PASSES THROUGH

BR TEST SCHEDULE REFERENCE IS 3.2.1.M
LOCATION IS RELAY ROOM LAS MUSAS
FOR THIS TEST TRAIN MOVES TOWARDS LAS MUSAS
SIGNAL ENGINEERS REFERENCE IS ATP LOOP
CALIBRATION REFERENCE NUMBER 4

TEST UNDERTAKEN ON 9 MARCH 83
CHOPPER EQUIPMENT BY AEG

THE FFT IS BASED ON 128 SAMPLES FOR THIS RESULT
WITH A FREQUENCY INCREMENT EQUAL TO 25.0HZ

Rectifier circuit arrangement and range of dc load current	Range of voltage components measured at specified frequencies, over load current range specified					
	50 Hz	100 Hz	300 Hz	600 Hz	900 Hz	1200 Hz
Single rectifier, single end feeding. 0 - 3000A	0.3 - 0.5	0.5 - 0.8	3.3 - 9.5	1.3 - 24.	0.3 - 10.	1.3 - 13.
Two rectifiers in parallel, single end feeding 0 - 3500A	0.3 - 0.7	0.7 - 2.0	0.3 - 9.2	0.5 - 2.2	0.1 - 11.	0.1 - 9.8
Two rectifiers, double end feeding 0 - 3800A	0.3 - 0.5	0.5 - 0.7	3.0 - 8.2	3.3 - 15.	0.5 - 4.6	0.3 - 8.5
Three rectifiers in parallel, double end feeding 0 - 7600A	0.5 - 0.7	0.5 - 0.7	3.0 - 8.2	2.6 - 18.	0.1 - 2.6	0.3 - 6.5

Table 1 : Range of power frequency harmonics measured in a 650V dc supply system

Rectifier circuit arrangement for particular test	Range of voltage components at specified frequency	
	50 Hz	100 Hz
Single rectifier, single end feeding	1. - 5.	7. - 12.
Two rectifiers in parallel, single end feeding	1. - 5.	3. - 10.
Single rectifier, single end feeding, broken arm fault	90 - 220	80 - 200
Two rectifiers in parallel, single end feeding, broken arm fault on one	3 - 17	19 - 28
Single rectifier, double end feeding	0.5 - 1.5	11 - 13
Single rectifier, double end feeding, broken arm fault on one	44 - 88	82 - 111
Single rectifiers as above but broken arm between two healthy rectifiers.	23 - 26	38 - 41

Table 2 Range of 50 Hz and 100 Hz components for tests in 1500V dc system with faults.

Number of trains in section of track considered	1	4	10
Peak chopper harmonic current at 528 Hz (A)	4.3	7.2	8.6
Peak supply frequency harmonic at 600 Hz (A)	3.9	6.6	8.1

Table 3 : Effect of the number of 6-car trains in section on the peak values of chopper and supply ripple components : 1500V system, L = 5 mH/2-car set

Reference position to datum (m)	RMS (mA)	50 Hz (mA)	250 Hz (mA)
-0.5	7	0.3	6
0.0	8	0.3	6.5
0.5	25	1.0	13
2.5	36	1.2	26
3.0	30	1.0	22
4.0	31	1.0	23

Table 4 : Illustration of direct coupling into relay end bond in a 50 Hz track circuit due to chopper action. Minimum 50 Hz pick up current is 140 mA

ELECTROMAGNETIC COMPATIBILITY TEST DATA FROM A MODERN RAPID TRANSIT SYSTEM

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1.0 Summary

Jointless audio frequency (AF) signaling is used in modern rapid transit systems. The trains are powered by direct current, usually derived from twelve-pulse solid state rectifiers and controlled by on-board solid state choppers. Electromagnetic compatibility between the signaling system and the traction power system is essential for safe and reliable operation of the transit system. This paper first outlines potential electromagnetic interference problems, some of which have actually been experienced in the recent past. Coupling mechanisms which couple energy from potential interference sources in the power system to susceptors in the signaling system are reviewed next. Recent refinements, both in the signaling system and in the traction control choppers are then described along with test data showing the current state of compatibility.

2.0 Interference Sources

There are many possible sources of electromagnetic interference (EMI) both within and from sources external to modern transit systems. However, the most likely are internal sources of EMI:

a) The traction power control choppers which are carried on board the train.

b) Traction power supply system.

Chopper controls in U.S. Transit systems are of three types. On one existing Property[1], the chopper operates at a nominal frequency of 400 Hz, but is programmed to start at a low frequency of about 120 Hz since at low vehicle speeds its output at 400 Hz exceeds the traction demand even at minimum pulse width or duty cycle. The chopper then sweeps at minimum pulse width to 400 Hz where control transfers to the pulse width mode. This transition occurs at a vehicle speed below about 5 mph. As speed increases the pulse width expands until maximum duty cycle is achieved at base speed. The chopper is turned fully on with further control of tractive effort being made via field control of the separately excited traction motors. The drive is capable of full regeneration with resistive braking blended to the extent that the traction power supply is non-receptive. During braking the chopper operates continuously with the frequency held constant at 400 Hz without sweeping.

A second type of chopper employing a pulse skipping technique is used on two recent transit systems. During starting it is switched on with a minimum duty cycle, and then one or more of the following chopper conduction periods are skipped as required for control of tractive effort[2,3]. The effective chopper period is therefore T, 2T, 3T,...., depending on the number of pulses skipped. Pulse skipping is on a preprogrammed schedule but the number omitted at any time is determined by the traction demand at the time. Similarly, during periods when required tractive effort is less than can be obtained at minimum duty cycle and during transition periods when the chopper is being turned full on, off periods are skipped to gradually increase tractive effort and avoid excessive jerk. In either case this chopper operates at subharmonic frequencies as opposed to the variable frequency operation of the frequency-sweeping chopper.

A third chopper type operates at about 400 Hz but steps to a lower frequency, usually 200 Hz to avoid excessive jerk during starting.

A typical substation for a transit system uses two or more six or twelve pulse solid state diode rectifiers with a combined power rating of two to ten megawatts[4]. In the U.S. two types of connections are widely used. One uses two separate 3-phase transformers with 30 degree phase shift supplying two separate bridge rectifiers connected either in parallel or in series. In the other configuration, a three phase transformer supplies two bridge rectifiers, again connected either in parallel or in series. Both of these arrangements result in 12-pulse rectifier operation having a dominant ripple frequency of twelve times the supply frequency or 720 Hz. Harmonics of this ripple in the audio frequency range may be of significant levels. Harmonic components are also seen at odd multiples of 360 Hz. Other components which are multiples of 180, 120, or 60 Hz may also be present, but normally should be at lower levels.

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3.0 Signaling System Susceptors

While one can speculate regarding the susceptibility of individual audio frequency signaling system components to various sources of EMI, in reality, the most susceptible parts have been found to be:

a) The wayside train detection receivers.

b) The cab signaling receivers.

AF track circuits operating in the range of 1 to 10 KHz are used both for train detection and to convey continuous speed commands to moving trains. AF jointless track circuits were developed several years ago to minimize the need for insulated joints previously used to define track circuit boundaries. Elimination of these joints reduced both acoustical noise caused by the wheels passing over them and the cost of maintenance prior to the advent of glued insulated joints. These AF circuits use electronic rather than electromechanical equipment to perform the track circuit functions. Figure 1 shows how signals are coupled to and from the rails by a single impedance bond (transformer), one of whose windings is connected from rail to rail. This winding also includes a center tap to provide for connection of traction return currents at supply substations and for cross bonding to adjacent tracks and/or return feeders at locations where such connections are made to increase the conductivity of the traction return network. Another isolated winding(s) on the impedance bond (Z-bond) is used for connection to the signaling system transmitters and receivers via appropriate coupling networks and cables.

The current permissible speed is displayed in the operator's cab of moving trains by sensing the character of modulation (coding) of the cab signaling current carried in the rails. This speed information indicates to the operator traffic conditions ahead of his train and, in the automatic train operation (ATO) mode, permits automatic regulation of the speed of the train. These functions must be carried out both safely and reliably.

The level of signaling currents in the running rails generally ranges between about 0.05 A and 0.50 A depending upon the application and signaling frequency.

4.0 Interference Coupling Mechanisms

The mechanisms by which interference from the various sources is coupled to the signaling system are described in the following paragraphs.

4.1 Induction of Chopper EMI into Track Circuits

The strong electromagnetic field present under the cars due to the chopper equipment and high current cabling may induce energy into the track circuit directly beneath the vehicle. The induced voltage in the rails under the vehicle results in a circulating current in the loop formed by the rails, the rear axle of the lead truck and the front axle of the trailing truck, as shown in Figure 2. This circulating current in the rails may be sensed by the signaling system as the vehicle passes over the Z-bond location. If the amplitude of the coupled interference is great enough and its other essential characteristics are sufficiently similar to a normal track signal, this can cause a momentary "unoccupied" indication, a potentially unsafe condition. Such a situation occurred on more than one transit system installation requiring system modification to allow satisfactory operation.

4.2 Conduction of Chopper and Traction Power EMI into Track Circuits

The propulsion current, containing harmonic EMI due to the traction power supply and the on-board chopper control, flows in the third rail and returns in the two running rails. If the return currents in the running rails are exactly equal, signaling equipment connected from rail-to-rail will not be affected. However, the return currents in the running rails are seldom equal due to unequal induction between the third rail and each of the running rails and some uncontrollable self inductance of the running rails. Thus, the propulsion return current in the running rails is unbalanced. The amount of unbalance is largely a function of the third rail placement with respect to the running rails and ranges to a maximum of about 34%. As shown in Figure 3, the unbalance propulsion return current can create an EMI input to the track circuit receiver. This can occur either when the track circuit is occupied as shown in Figure 3(a) or when unoccupied as shown in Figure 3(b). In the occupied case, if the unbalanced ac component (i1-i2) creates enough interference within the pass band of the signaling system and if its character is sufficiently similar to that of a normal track signal, it could create a potentially unsafe condition by falsely energizing the track circuit relay. In the unoccupied case, a disruption in service would result if the track circuit produced a false occupancy condition caused by EMI energy overriding the normal track signal.

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5.0 System Improvements

Since chopper control systems were first introduced into transit systems about five years ago, there has been a concerted effort by suppliers of both choppers and signaling systems to mitigate interference problems.

5.1 Chopper Design Improvements

Two specific improvements were made in the design of the chopper used in the most recent new transit systems.

a) Chopper hardware and cabling were designed to minimize the intensity of the external induction field under the car with the aim of eliminating "induced case" interference.

b) The chopper line filter in the third rail feed aboard the car was modified to improve harmonic attenuation thus reducing the intensity of potential interference conducted to the track structure.

5.2 Signaling System Improvements

AF signaling systems intended for operation in the presence of the strong chopper-generated induction field under the car must be capable of discriminating between interference and the real track signal. To accomplish this requires that the signaling system utilize characterized signals which are sufficiently dissimilar to the character of interference as to allow satisfactory separation by the receiver circuitry. Early AF jointless signaling systems, which were designed prior to introduction of choppers, were not capable of the required separation; thus it has been necessary to develop a new generation of signaling equipment.

The signaling system used on the two newest transit Properties makes full use of the characterization provided by the coding inherent to the track signals. Whereas earlier systems used a form of broad band signal decoding, the new system uses narrow band filtering and a synchronous rectifier decoder which provides phase comparision of the transmitted and received codes.

6.0 Test Data

Results from both induced and conducted interference tests on one of the newest transit Properties are presented below.

6.1 Induced Interference

As a train passes over a Z-bond location the track circuits should continue to present the occupied indication until the last axle has cleared the circuit. The large electromagnetic induction field under each transit car has the potential for causing a false unoccupied indication if the signaling system does not satisfactorily reject the false signals. Figure 4 shows a high level of interference seen at the receiver input, in the absence of normal track signal, when a two car train passes over a Z-bond. Note that the level is several times that of a normal track signal.

Figure 5 is a similar plot showing the variation in normal track signal level as a train approaches and passes over a Z-bond location. The carrier is 3870 Hz. Note that the level gradually decreases as the train approaches the transmitter end of the track circuit. It reaches zero when the first axle shunts the Z-bond. The level gradually increases again as the train leaves the receiver end but this is obscured by induced interference. As each car passes over the Z-bond, a large burst occurs due to the induction field. The level of this burst in this figure was clipped by the instrumentation so that its true magnitude is not shown. However, a comparison with Figure 4 shows that the burst magnitude is at least twice as large as the normal signal. Figure 5 also shows a plot of the synchronous rectifier output. As may be seen, the level falls to essentially zero and remains there even during the period of the large interference from the induction field. The track relay remained de-energized, thus demonstrating rejection of induced interference.

6.2 Conducted Interference

Interference conducted through the running rails has the potential of disrupting normal operation of both the wayside train detection and cab signaling functions.

6.2.1 Wayside Train Detection.

The synchronous rectifier detector used in the track circuit receivers effectively rejects foreign signals. The remaining concern is reduced reliability due to safe side failures caused by interference overriding the normal track signal. Figure 6 is a plot of a normal coded track signal without the effects of interference. Note that there is little or no interference mixed with the signal, as is evident from the zero level during the code-off periods.

Figure 7 is a plot of in-band receiver signal as a train approaches a track circuit. It shows coding of the carrier and the roll-off as the train arrives at the Z-bond. Note also the increasing level of fill-in during the code-off period as the train approaches the Z-bond. This is due to conducted interference which changes as a function of train location. The magnitude of this interference is also affected by the impedance of the traction power supply and distribution network. Since the traction feed was at the track circuit entering end Z-bond immediately in front of the train, the interference is near worst case in this plot.

A spectral plot of a 1590 Hz receiver signal is shown in Figure 8. The carrier and sidebands are the large components spaced at 16 Hz intervals across the plot. The large component at 1560 Hz (to the left of center, between the first and second sidebands) is a harmonic from the traction power substation. The usual array of traction power harmonics from a twelve-phase rectifier supply would be expected at 720 Hz and its multiples with lesser components at 360 Hz and its odd multiples. Any components in or near the 1590 ± 30 Hz pass band should be small. The other components scattered across the plot are of unknown origin, and are probably associated with the presence of interference.

6.2.2 Cab Signaling.

The cab signaling receiver is equipped with a carrier filter tuned to 990 hz and with a series of code rate filters to select speed commands according to the code rate with which the cab signal carrier is modulated. The most likely failure mode with regard to interference is that the normal carrier may be overridden by interference, causing an operational reliability or safe side failure.

The level of the coded 990 Hz cab signal current in the running rails is smallest when the train first enters a given track circuit. It increases gradually as the train proceeds through the circuit as shown in Figure 9, reaching a maximum value at the leaving end which is determined, in part, by the length of the circuit. Note that there is very little signal during the code-off period indicating that there is no significant interference in this data sample.

The cab signal receiver uses a carrier filter having a bandwidth of about 42 Hz. Thus, power supply harmonics which are expected at 720, 1080 and 1440 Hz are far enough removed from the pass band that they are well attentuated. Figure 10 is a spectral plot covering the frequency range from 700 to 1500 Hz. As may be seen from this Figure, all three harmonic components are at levels at least 50 dB below the coded carrier. This indicates that there should be no significant interference to operation of the cab signal system from harmonics of the traction power supply.

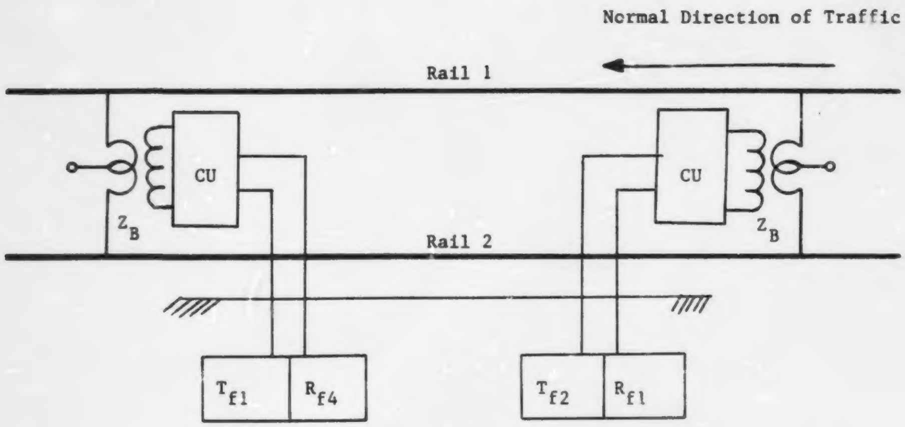
Figure 11 is a similar spectral plot but over a narrower frequency range from 950 to 1030 Hz. Of course there are no power supply harmonics within this band, but the filled-in area at the bottom center of the plot was caused by chopper pulse skipping. The level of this interference in the test represented by this data is not significant relative to disruption of normal service.

7.0 Remarks

This paper has reported the latest chapter in the ever changing story of rapid transit system electromagnetic compatibility by means of field test data gathered on a new system which has recently been placed in regular service. It is the follow-up a of paper[5] presented on the subject at the 1982 Joint ASME/IEEE Railroad Conference. Further background regarding the compatibility question may be obtained from that paper. It is hoped that the data presented here will lend future perspective to the subject of AF jointless signaling electromagnetic compatibility with transit system EMI environment.

References

1. J. Hoelscher, R. Rudich, "Compatibility of Rate-Coded Audio Frequency Track Circuits with Chopper Propulsion Drives", Paper presented at the International Conference on Railways in the Electronics Age, IEE, London, November 1981.
2. Donald E. Stark, "Conducted Interference Update: AF Signaling, Chopper, and Traction Power Systems", paper presented at the Signal Session of APTA Annual Meeting, Chicago, IL, October 8-11, 1981.
3. Vilas D. Nene, "Electromagnetic Interference Characteristics of Advanced Propulsion Systems for Urban Rail Vehicles", Final Report No. UMTA-VA-06-0075-81-1 prepared for U.S. Department of Transportation, available from NTIS, Springfield, Virginia 22161.
4. Vilas D. Nene, "Harmonic Characteristics of Rectifier Substations", paper presented at International Conference on Railways in the Electronics Age, IEE, London, November 1981.
5. Donald E. Stark, Chinnarao Mokkapati, "Electromagnetic Compatibility Assurance for DC Propulsion Control Choppers, Traction power Supply and Signaling Systems", paper presented at the 1982 Joint ASME/IEEE Railroad Conference, April 19-22, 1982, Erie, PA.


Normal Direction of Traffic
Rail 1
CU
CU
Z_B
Z_B
Rail 2
T_{f1}
R_{f4}
T_{f2}
R_{f1}

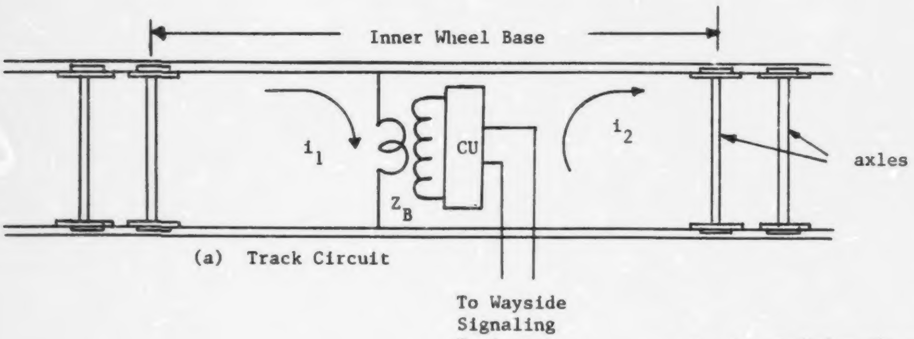
Z_B: Impedance Bond

CU: Coupling Unit

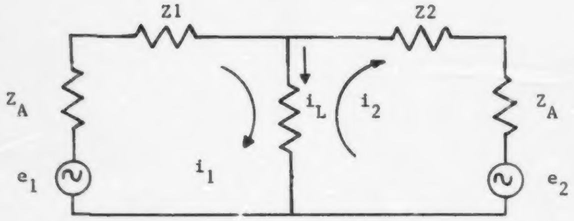
R_{f1} = Receiver of frequency f1

T_{f1} = Transmitter of frequency f1

Figure 1. Audio Frequency Jointless Track Circuit (Frequency: f1)


Inner Wheel Base
i_1
CU
i_2
axles
Z_B
To Wayside Signaling Equipment

(a) Track Circuit


Z1
Z2
Z_A
i_L
i_2
Z_A
e_1
i_1
e_2

(b) Electrical Equivalent Circuit

e_1, e_2 = Induced Loop Voltages

i_1, i_2 : Circulating Loop Currents

Z_1, Z_2 : Track Impedances

Z_A : Axle Impedance

Z_L : Signaling System Input Impedance

$i_L = i_1 - i_2$ = Interference Current through Signaling System.

Figure 2. Induction of Chopper EMI into Track Circuit.

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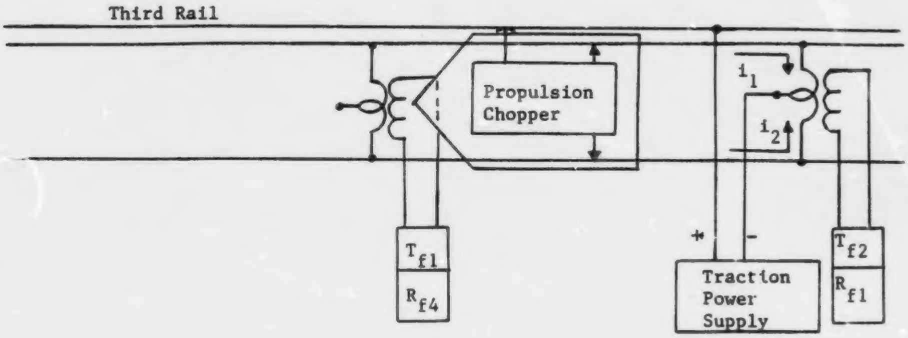
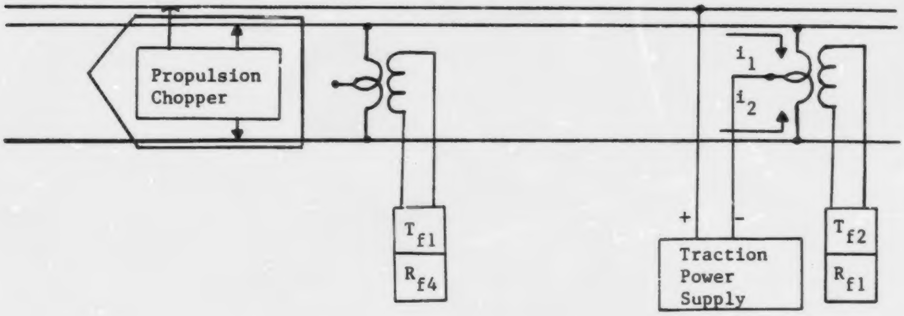


Third Rail
Propulsion Chopper
i_1
i_2
+
-
T_{f1}
R_{f4}
Traction Power Supply
T_{f2}
R_{f1}

(a) EMI in Occupied Track Circuit



Propulsion Chopper
i_1
i_2
+
-
T_{f1}
R_{f4}
Traction Power Supply
T_{f2}
R_{f1}

(b) EMI in Unoccupied Track Circuit

i_1 and i_2 are ac components of traction return current

Figure 3. Conduction of Chopper and Traction Power EMI into Track Circuits.

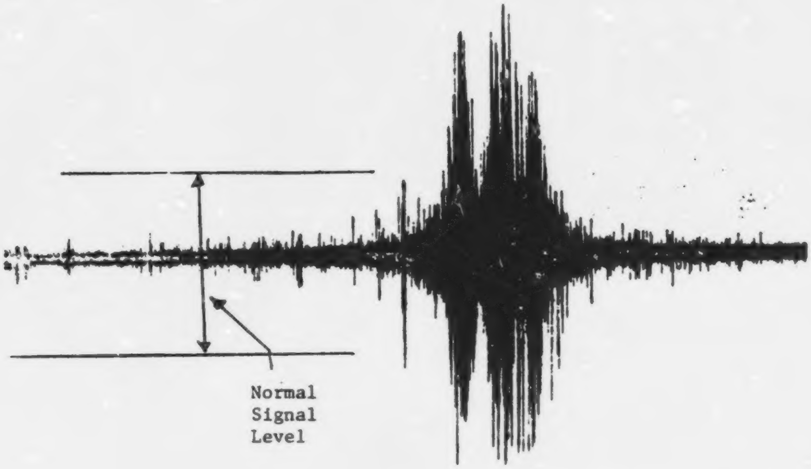


Figure 4. Induced Interference from a 2-car Train in the Absence of Normal Track Signal.

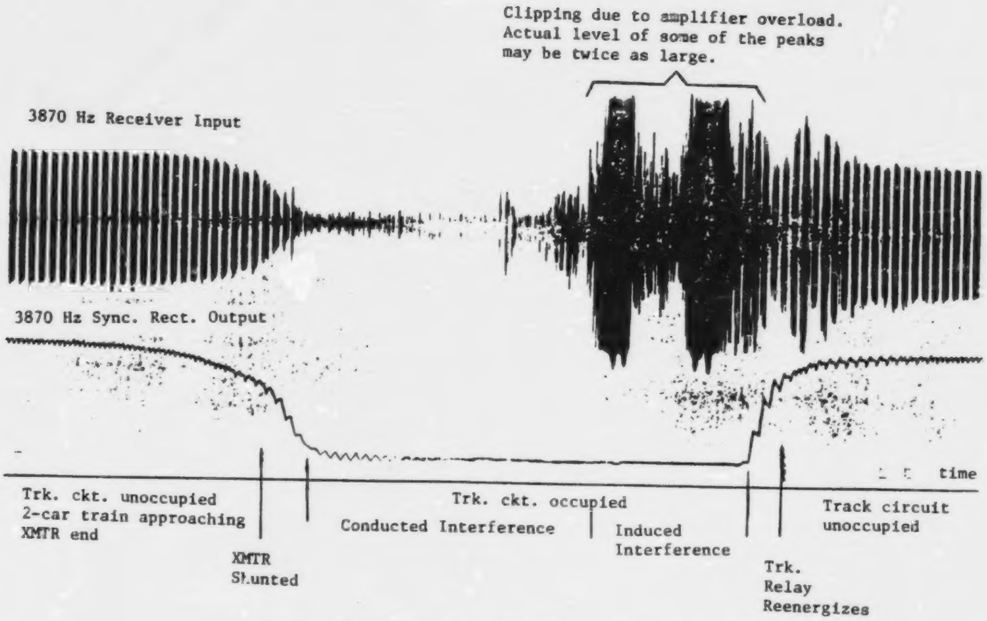


Figure 5. Normal Track Signal plus Interference from a 2- Car Train.

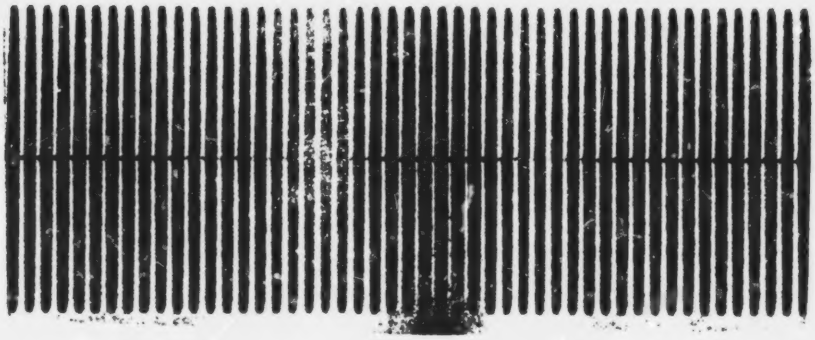


Figure 6. Normal Coded Track Signal Without Interference

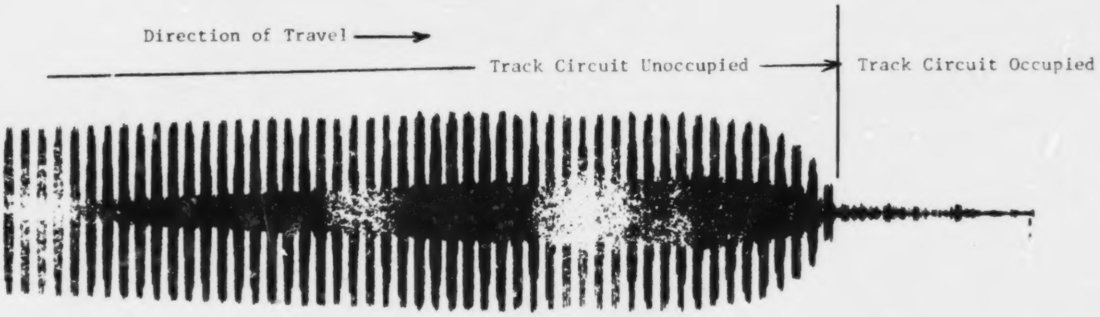


Figure 7. Conducted In-band Interference Mixed with Normal Coded Track Signal

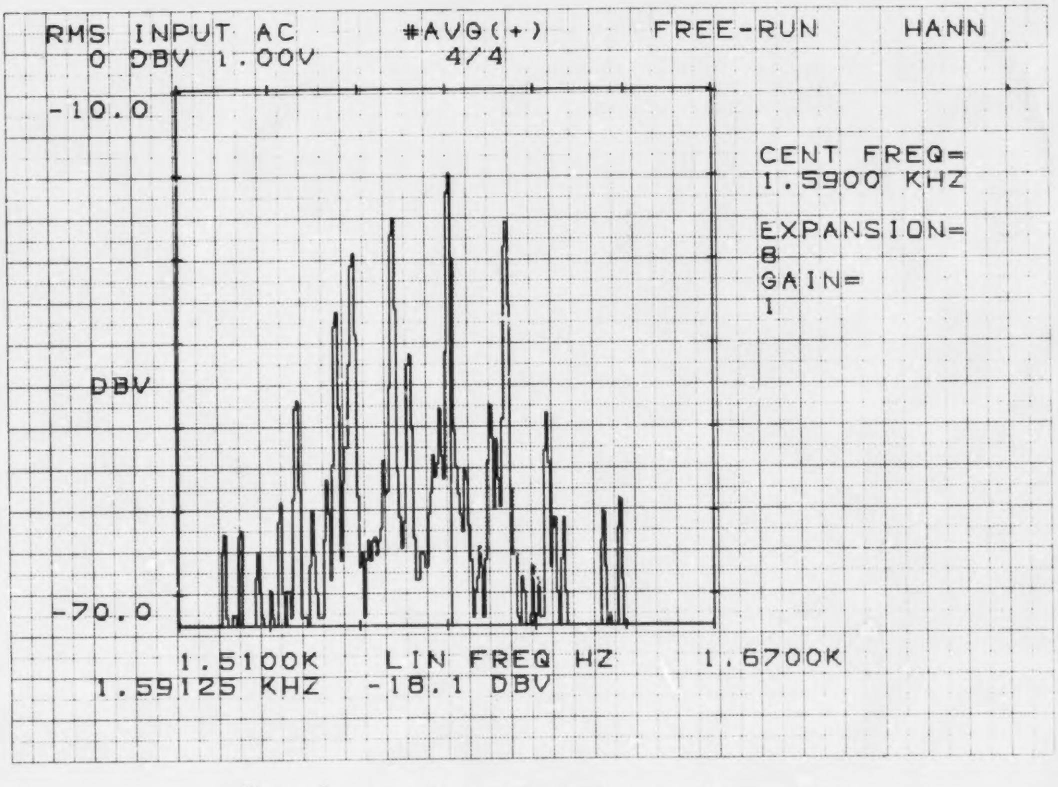


Figure 8. Spectral Plot of Signal + Interference Shown in Figure 7.

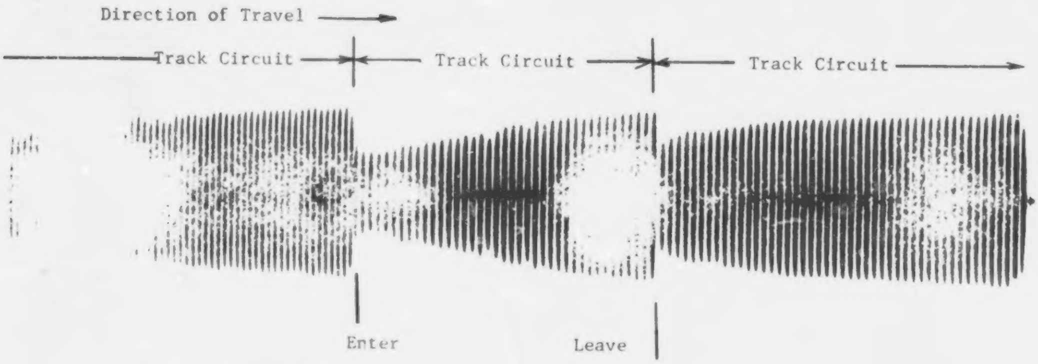


Figure 9. Variation of Normal Cab Signal As Train Travels Through Track Circuits

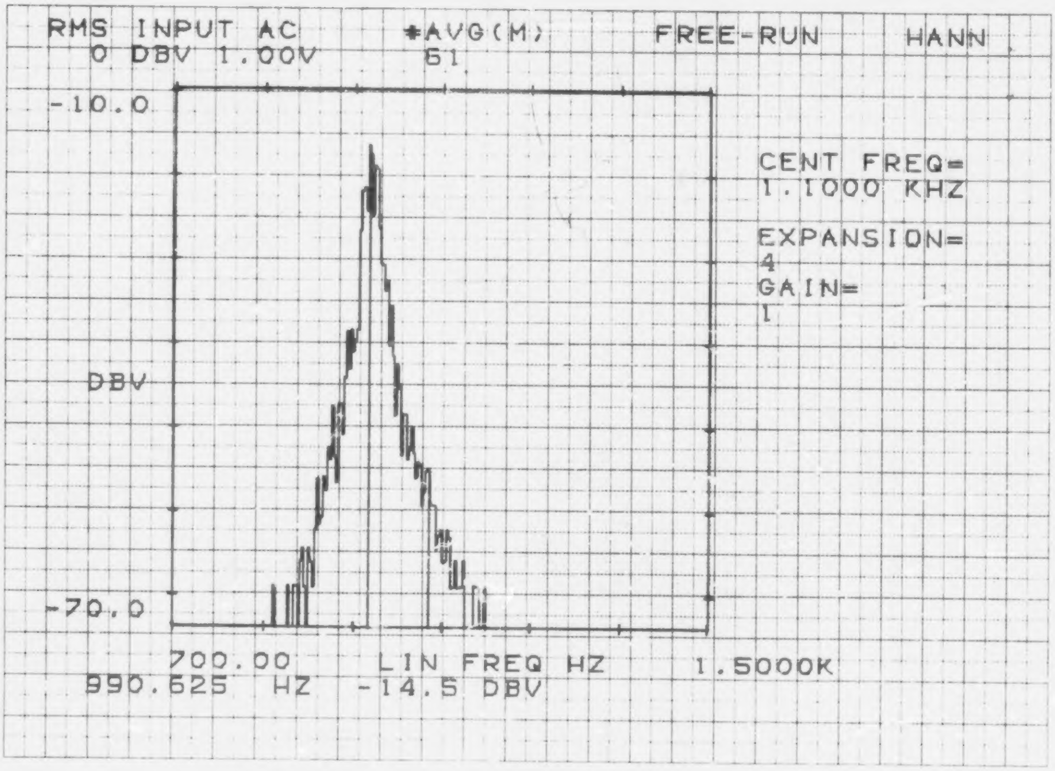


Figure 10. Spectral Plot of Cab Signal (700-1500 Hz Window)

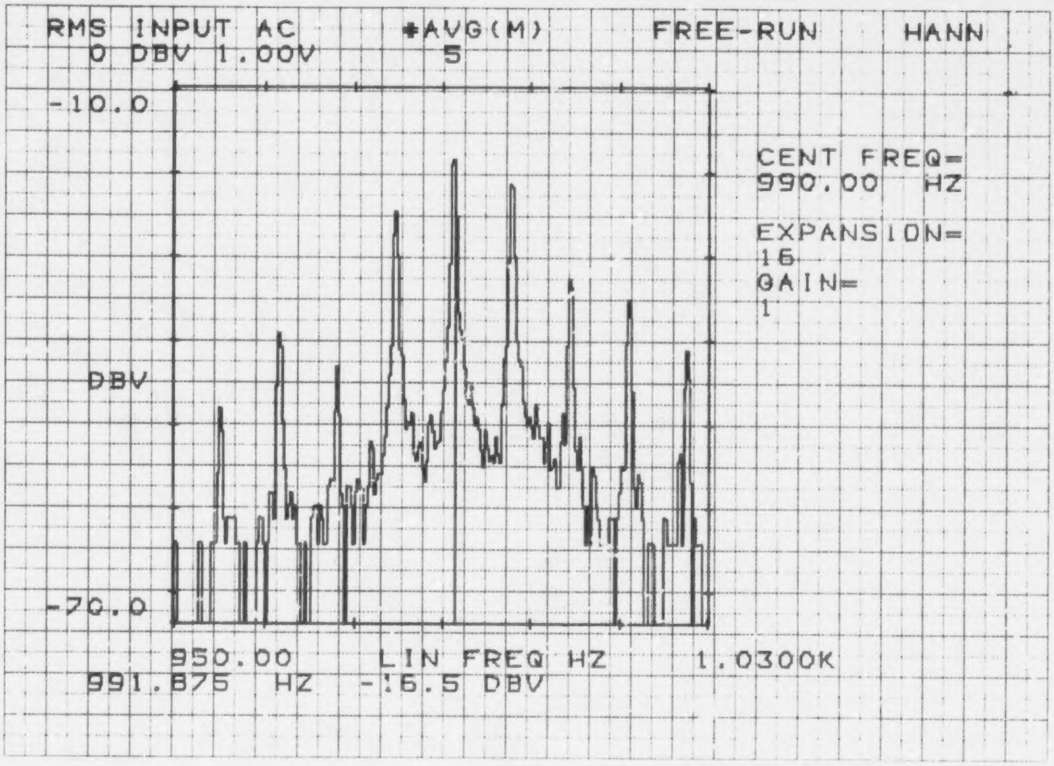


Figure 11. Spectral Plot of Cab Signal (950-1030 Hz Window)

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VITAL MICROPROCESSOR

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Vital Microprocessor Abstract

This paper is an overview of Union Switch and Signal's concept and implementation of a single microprocessor for safety critical applications.

Vital single microprocessor philosophy utilizes closed loop principles. These principles are implemented with DUAL PATH programming techniques and WRAP AROUND discrete hardware. The DUAL PATH programming and its associated diagnostic routines are controlled by SOFTWARE. The majority of the discrete, WRAP AROUND hardware is not intrinsically vital. However, this hardware when interfaced and controlled by the microprocessor, is made vital by the SOFTWARE "LOOP BACK" MONITORING techniques developed for these vital applications.

Field applications of this philosophy have been demonstrated with the installation of the Micro-Code system. The Micro-Code system uses the rails as the transmission link to provide vital train detection as well as block ahead status, traffic and other vital and non vital information.

1.0 Introduction

As we all know, the 1970's and 1980's have been marked by rapid and numerous changes in technology. The computer revolution has touched almost every facet of our daily lives. These technological advancements will continue to play a dominant role in the future of railroad and rail rapid transit signaling and control systems.

With the evolution of the microprocessor, we have seen phenomenal progress in railway control applications. With the use of the microprocessor, we can now place "intelligence" in almost any device, location or system. Over the past five years we have seen the microprocessor used in a variety of railroad and transit applications.

For example, microprocessors are used in communications and code systems, in automatic vehicle identification, in office logic, in cab signaling, in automatic train control and supervision, in event recorders, and in train describer and local control panel displays.

These products are devices which use digital data transmisssion with appropriate microprocessor hardware and software providing the logic for system operation. However, the application of the microprocessor to traditional transportation products has only begun.

2.0 Learning From the Past

The rapid advancements in technology over the past 10 to 15 years has resulted in a challenge presented to the signaling community. This challenge is simply stated as "can vital relay devices and circuits be replaced with high technology devices and still maintain the safety level that currently exists for relay control systems?"

The major thrust to replace relay-based control systems is economics. The smaller and more efficient microprocessor-based system will be easier to maintain, require less energy, and be more reliable, and the manpower to operate the system will be reduced. The potential for cost savings is phenomenal.

Once the decision to replace traditional relay systems with high technology devices is made, a natural question arises: Can we learn from the past?

Traditionally, signaling systems have evolved through years of historical data collection on designs and concepts that work very well in terms of providing safety.

Do we ignore these years of proven circuit logic and concepts? Union Switch and Signal's answer to this question is no!

We can make use of the years of collected circuit logic and design principles. Implementing these past design principles with this new technology can be illustrated by defining:

- Operational software
- Hardware configuration
- Diagnostic software

2.1 Operational Software

Operational software is the means of identifying and implementing the required logical decision making of the system. Using the "past" insures "the correct" contacts/functions are implemented for safety reasons. These traditional logic conditions are "stored" in the form of "standard circuits" and are familiar to the signal engineer. Thus, to enhance operational safety, a simple means of translating these "standard" circuits into program code for the microprocessor is required.

How can this be accomplished with a microprocessor-based system? Does the railroad have to hire a staff of programmers to make modifications or updates to his system? The implementation of control logic in a microprocessor should be accomplished so that the skills of the existing relay designer can be fully utilized. One method of accomplishing this is through the use of a high-level language compiler. A compiler is a computer program which translates instructions written in a higher-level symbolic language into machine language. Hence the compiler permits the signal engineer to describe his logic design in common terms which can be equated to the original relay designs he is familiar with. The compiler merely converts the logic into a tabular form which the microprocessor can understand.

In a sense the designer can use his relay circuit as a flow chart for the logic functions he wishes to perform. First the relay circuit is designed, then the logic is described in simple-to-understand English text or Boolean algebra. The text description is then submitted to the high level language compiler. And finally, the compiler converts the logic described from text format into a form which can be executed by a microprocessor-based system.

Using the relay based system as our model, we also have requirements for various timing considerations to be implemented. In a similar manner the logic description can specify the pickup and release times of the logic elements at the start of the design. The actual timing will be accomplished automatically each time the microprocessor encounters the logic element during program execution.

Designs done in this manner also have the advantage that they require no optimization as their relay counterparts do. Contacts in the relay design must be assigned for repeaters because there are a limited number of contacts per relay. However, in the microprocessor design, contacts are simply added as required to complete the desired logic function. Essentially, the designer has the freedom of assigning as many contacts as are required to accomplish the design. One of the major advantages to this approach is that all logic interconnection which was once done with wiring in the relay system is now done in software. This makes modifications or updates very easy to accomplish. Another advantage is that sneak paths which may have existed in the wired logic potential are minimized with the microprocessor logic. The microprocessor executes each logic statement in a sequential manner.

Using this method, the designer need not understand the microprocessor system or how to program. He only needs to understand the logic for the application he is designing. It provides both a convenient and an efficient method of microprocessor-based logic. The railroad as well as the supplier does not have to retrain their personnel to understand the microprocessor, nor do they have to hire a software programming staff to update and maintain their new systems.

2.2 Hardware Configuraton

Now that we have maximized the use of traditional logic configurations to enhance operational safety, can we extract from traditional signaling principles, concepts that can be implemented with the new technology? The answer to this question is yes!

Traditionally we have used vital relays to implement safety critical circuits in signaling. In principle, these circuit designs rely on the "closed-circuit" and "closed loop" techniques which are familiar to all of us.

For example, traditional vital closed-circuit functions such as the following must be incorporated in the new microprocessor technology:

- Traffic locking
- Approach locking
- Detector locking
- Route locking
- Time Locking
- Switch correspondence
- Signal control networks
- Etc., relative to interlocking and/or automatic block signaling techniques

These traditional design concepts can be implemented (and in some cases improved) with the new technology. In a few minutes we will see how these design concepts are implemented with the new technology.

Union Switch and Signal has developed a concept for the use of a single microprocessor in safety critical circuits. Other designers are investigating/implementing multiple processor arrangements with a voting scheme to achieve safety. However, with the design of the proper check techniques and hardware/software combinations, safety can be achieved with either a single or a multiple processor approach.

We have developed a single processor concept because this approach results in less hardware.

The concept of a single microprocessor used in safety critical circuits encompasses the use of closed-loop principles. Implementing these principles is accomplished with the use of DUAL PATH PROGRAMMING techniques with "WRAP AROUND" discrete hardware. This concept maximizes reliabiilty and flexibility while minimizing hardware and maintenance requirements. In addition, the use of redundant systems with auto changeover with alarms results in maximizing system availability without the use of redundancy for safety. Dual path programming refers to the interleaving of diagnostic routines and system checks within the operational software data base. The majority of the discrete, wrap around hardware is not intrinsically vital in design. However, this hardware, when interfaced and controlled by the microprocessor, is made secure by the software "loop back" monitoring techniques developed for these vital applications. One example of this technique is input/output monitors. The processor talks and listens to these devices. The processor "toggles" the input and output monitor devices and requires a given response from these devices.

With this type of arrangement, there is no need to require the input and output devices to fail in only one predictable state. The use of the "toggle" signal results in the safe-side condition if the device(s) fails in any state. This monitored signal will alert the microprocessor to the failure so that additional corrective action can take place.

This concept is identical to some of the traditional, relay- based, closed-loop principles. For example, the vital relay logic and devices used to check that a switch position agrees with its requested position and is locked prior to permitting a train movement to be signaled over it.

2.3 Diagnostic Software

A block of vital hardware that is interfaced to the microprocessor is the conditional power supply. This device generates a DC output voltage only when a "correct" input signal is received.

The vital conditional power circuit supplies DC energy to the output devices if a vital clock signal is present at its input. The vital clock signal is derived from the internal diagnostic routines resulting from the dual path programming techniques and internal checks. Failure to pass the diagnostics or system checks results in removal of power from the output device.

This removal of power is related to the traditional concept found in vital relay logic. Energy removed from a relay coil results in a safe-side condition. For example, a switch is "locked" by de-energizing the "lock" relay. The traditional relay logic circuit principles (closed-loop) are implemented by requiring "front" contacts to be closed to perform a function that is related to safety. This concept results in a safe-side condition if wires open, relay coils open, or power is removed. For example, a track circuit is said to be unoccupied if its associated track relay is energized. If, for some reason, a wire opens, contacts fail, etc., the logic state of this function results in the occupied condition: a safe-side state.

This concept is also implemented with the new technology. The presence of a logic state is required to perform a function that is related to safety. These logic states are a natural outgrowth of copying the traditional relay logic circuits.

3.0 Failure Modes

The technique of dual path programming with wrap around closed-loop hardware results in the detection of failure modes of a safety critical system. The failure modes are monitored by internal diagnostic routines. These routines include such tests as the CPU internal registers, operational codes, PROM checks, RAM checks, continuous cyclic up-dates, input/output address tests. input/output monitor tests, read/write sequences, dual timer comparisons, and vital time base and frequency checks.

In addition to these tests, a specific hierarchy of testing is performed to enhance safety. One example of this hierarchy of testing is the OP code test.

The OP code diagnostic test results in a family of OP codes being proven "good" and those in turn are used to check other OP codes. In addition, the sequencing of all tests must be done in a specific time frame.

4.0 Maintenance

From a maintenance and service stand-point the problems of the microprocessor-based systems have not only placed an enormous burden on the railroad but also on its suppliers. Today it's not uncommon to see 30 to 50 year old relay-based control equipment interfaced and operating with high tech systems which employ microprocessor technology. The hiring and maintaining of a suitable service force with the necessary skills and test equipment to maintain this combination of past and present technologies is an enormous task.

Because of the difficulty in maintaining these high tech systems, many railroads have opted for the quickest solution to returning a nonfunctional system to operation; board swapping. Although this may be the quickest solution, it definitely is not the most efficient! It creates several other problems for the railroad. One problem is that along with the bad boards that are swapped out of the system, a large percentage of good boards are also removed. The combination of good and bad boards creates a service problem for the technician attempting to determine if a board is operational or not, in addition to increasing the railroad's inventory by requiring a large number of spare boards for each system in service. For a typical system, there may be many good boards in the shop waiting to be tested before they can be returned to service.

It's very apparent that a new approach to maintenance is required to deal with these new high tech systems. One solution is the use of the existing microprocessor within a system to diagnose its own faults. The diagnostics can simply be designed as a "GO" or "NO GO" test or they can be designed to isolate a failure to a single board, or even to the level of a component on the board. Once it's determined which board or component has failed, it is a simple matter to correct the problem by replacing the defective unit. Using the microprocessor as a self-test device to determine system failures, visual indications through the use of LEDs can provide the maintainer with information on proper operation or indentify a failure within the system.

5.0 Applications

Vital logic has been done traditionally with relays. However, Union Switch and Signal pioneered the use of solid state vital logic in car carried cab signal/overspeed systems dating back to 1967 when Montreal's Expo Express first used such equipment.

A recent product that incorporates the microprocessor techniques just described is Union Switch and Signal's Micro-Code track circuit.

Micro-Code is a system that uses the rails as the transmission link to provide vital train detection as well as block ahead status, traffic and other vital or non vital information. Micro-Code alternately transmits pulses of opposite DC polarity, varying the time length of selected pulses to establish a code pattern. Micro-Code is a half-duplex system based on the master-slave principle.

The Micro-Code track circuit uses a conditional power supply to energize the output devices, and input and output monitor devices that are interfaced to the processor and toggled. The dual path programming and wrap around hardware, together with the internal diagnostic software routines, enhance the safety of the device.

Over 60 miles of revenue service track are controlled by Micro-code system on the N&W Railroad, in addition to 40 miles of service on the SP.

6.0 Summary

The next few years will be very exciting. The acceptance of the microprocessor into traditional control functions will play a dominant role in the future of railraod and rapid transit signaling and control systems.

CHECKED REDUNDANT MICROPROCESSORS IN CARBORNE TRAIN CONTROL APPLICATIONS

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Westinghouse Transportation Division
USA

Summary

This paper will describe the use of checked redundant microprocessors in the equipment of the Westinghouse Transportation Division. The applications of this technique is discussed generally and for specific areas such as speed decoding and overspeed detection. The mix of functions between hardware and software has evolved since initial Westinghouse equipment was designed in the late nineteen sixties. This evolution is explored through such programs as Bart, Sao Paulo, Atlanta Airport and the latest designs for Sao Paulo and Bart to establish the rational and possible future trends for this important design area.

General System Overview

The Westinghouse automatic train control systems of the past have shared a common set of basic operating functions. The entire system consists of the major sections of central control, interlocking, local station, wayside location and vehicle functions. For this discussion we will be concerned primarily with the vehicle safety functions related to speed decoding and overspeed detection.

The shared portion of all our systems in this safety area has been the speed code system utilizing a 6-bit comma-free code generated by the local station equipment. Through a time division multiplexing scheme, the speed command signals are transmitted to the individualized wayside blocks. The signals associated with each wayside block serve the dual function of providing occupancy determination of the track circuit and providing a speed command for the train. It is with this latter function that we shall deal in detail.

The speed command comma-free codes used in Sao Paulo are shown below in Table 1.

Code	Speed
100000	0 kph
100001	10 kph
101001	30 kph
100101	44 kph
100011	62 kph
101011	75 kph
100111	87 kph
101111	100 kph

Table 1

The use of comma-free codes allows continuous transmission of the code and minimizes the response time of the vehicle to changes in the speed code. The code structure is such that a loss of a "1" will result either in a lower speed code or an invalid speed code; neither of these being unsafe.

The code transmission itself uses a frequency shift keying (FSK) mechanism. Four distinct frequency pairs are used for the signalling. One pair is used for each individualized wayside block, and adjacent blocks use different pairs of frequencies from the choice of four pairs. The frequencies are in the range of 5 to 10 kHz, and the 6 bit speed code is sent at a rate of 18 Hz i.e., each bit of the code is present for 1/18th of a second.

The train receives the FSK signal from the rails through a set of antennas mounted in front of the train. These antennas must be mounted in front of the leading axle of a steel-wheeled train since the shunting effect of the axle is an integral part of the wayside train detection (block occupancy) scheme. Hence, the signal behind the axle is essentially reduced to a non-detectable level. In the rubber-tired systems, this same rail-shunting function is performed by a set of vehicle mounted brushes riding on and shunting out two signal rails mounted between the concrete running surfaces.

The train speed is controlled by comparing the commanded speed, received as a speed code from the wayside signalling rails, with the actual speed as measured by axle-mounted tachometers. The resulting comparison represents a speed-error which is used to control the operation of the propulsion and braking systems.

There are other functions being performed by the vehicle equipment. Some of these are speed maintaining, door control, program-stopping, information system transmission and reception, performance modification and console display. Among the functions listed above are a few that are safety related. However, for the purposes of this paper, the focus will be on the speed maintaining and speed decoding functions in order to illustrate the application of checked-redundant microprocessors in the realm of safety controls. The principles developed will be applicable to the other functions.

General Methods of Safety Implementation

It is important at this stage to discuss the tools which are now available to a system designer for implementing safety related functions. Basically, there are three "pure" approaches and numerous shadings of these "pure" approaches when they are used in combination with one another.

First, circuits to be used for safety functions can use vital components. The beauty of this approach is that the unsafe failure modes of the devices are so improbable that they can be assumed not to occur. In practical situations proper preventative maintenance procedures must be performed to ensure the integrity of the devices safety. The vital relay utilized in railroad interlockings is such a device.

Second, circuits to be used for safety functions can use non-vital components. However, these non-vital components must be arranged in a system structure which provides checked-redundancy of the vital signal pathways and functions.

Third, circuits to be used for safety functions can use logic elements of a non-vital nature. Essentially, this method is the same as the one above except computers and software technology are used within the checked-redundant framework.

Throughout Westinghouse's history with transit systems, there has been an evolution from the pure use of vital components to the present blend of all three methods. The original Bart system employed the method of vital components to fulfill its design goals. Vital relays, vital logic gates and charge pumps provided the building blocks to implement the functional vital subsystems.

The first use of microprocessors in a safety application occurred for the 108 Car Add-on order in Sao Paulo. This equipment shared all three approaches in the safety design. The emphasis was away from vital components so that the versatility and flexibility of the microprocessor could be utilized.

The latest vehicle equipment design for Bart will swing further toward the use of non-vital logic in a checked redundant fashion. Many of the sub-functions incorporated in Sao Paulo as non-vital components have been pulled into the microprocessor. Among these are portions of door control, speed-error and balance detection and the startup function which temporarily overrides the tachometer circuit.

It is important at this point to further explore the fundamentals of checked-redundant design. Mathematically the evaluation of any safety design depends on quantifying the Mean Time Between Unsafe Failure (MTBUF). For the commonly used AAR-type safety relay, the MTBUF is about 10^6 years. It is recognized that not all functions can be implemented with fail-safe components. In these situations, redundancy is commonly used. In other words, two or more sets of circuits doing essentially the same thing are used. Using such a strategy, the designer must still keep in mind that the MTBUF must be kept to an acceptable level.

Once the choice is made to use redundancy in a design, certain requirements are implied to make the design safe. Unlike the fail-safe design, the redundant design has certain combinations of failures which could be unsafe. Thus it is necessary to check the integrity of each redundant pathway to ensure the probability of an unsafe condition has been reduced to an acceptable level. By checking the integrity of the redundant channels periodically, the safety of the system can be reconfirmed. The more often the check is made the larger the MTBUF becomes.

Implied in the use of checked-redundant design are a few overall guidelines. These guidelines were outlined in the Battelle safety study report on the Sao Paulo 108 equipment.[1] First, the designer must guarantee independence of the redundant channels. This is important to ensure the nature of component failure is random. The things which must be avoided include compensating failures in which a failure in one channel causes failures in another. Another thing to avoid is the possibility that a single event such as temperature, transients or mechanical shock does not cause simultaneous failures in both channels. Such a situation could produce the same incorrect output from both channels. This would be undetectable and thus potentially unsafe.

The detection of failures is the second guideline to be used. Any safety related failure of a redundant channel must be detected. The key to this guideline is that even though the equipment can continue to operate safely after the failure, the safety of the system is now dependant on only one channel and the chance of a similar failure in that channel. Thus, the detection of the potentially unsafe failure in one channel must result in appropriate action.

This leads to the third guideline which requires action on detection of a failure. The "promptness" of the response to a failure must be consistent with the overall system safety stopping profiles. In addition, resumption of service of the vehicle must either be after repair of the failed unit or after switching to a restricted mode determined to be safe through previous analysis.

The fourth guideline is that the MTBUF for the combination of redundant elements must be equivalent to that provided by fail-safe technology providing the same function. A standard proposed is the evaluation of a design by comparing it to an equivalent design using AAR safety relays. Though this evaluation is somewhat subjective, the intention is worthwhile.

To conclude this section, the mathematical formulae for the concepts discussed above will be presented.

First the probability of a failure in both channels of a two channel redundant system within a given time period is

$$Ps(t) = \lambda s \cdot \Delta t \text{ and } MTBUF = \frac{1}{\lambda s}$$

where $\lambda s = \lambda_1 \cdot \lambda_2 \cdot \Delta t$ and

$\lambda_k = \frac{1}{MBTF_k}$ (the failure rate of each channel). Combining all of these, the summary formula is obtained.

In the sections of this paper to follow, the implementation of the concepts developed above will be discussed for specific hardware and software designs.

Use of Checked-Redundancy in Hardware

In this section, the hardware configuration of the Westinghouse Transit Systems will be outlined. This view will focus on the general configuration of the hardware and the use of checked-redundant structures. The use of software techniques to implement some of the checks will be explored in another section.

As stated previously, the Westinghouse designs have evolved around a core concept of speed decoding and overspeed protection. Though the designs have moved from a hardware to a software emphasis, the same basic structure allows discussion of a generic design using the same terms from the original Sao Paulo 108 cars to the new Bart designs.

The Automatic Train Protection (ATP) system on the vehicle can be divided into five subsystems.

1) Speed-Code Reception and Decoding Subsystem
2) Tachometer Processing Subsystem
3) Speed Error Generation Subsystem
4) Vital Interface Subsystem
5) Propulsion/Brake Interface Subsystem

Speed Code Reception and Decoding Subsystem

The Speed Code Reception and Decoding Subsystem consists of antennas, preamplifiers, switches and receiver circuit. The antennas consist of two assemblies, one mounted on the left side and one on the right side at the front of the vehicle. Each antenna contains two coils. This redundancy is for reliability not safety. One coil from each side is fed to a preamp clipper which provides the gain and matching necessary. The preamp clipper is of vital design. This is necessary to insure that no failure modes can cause the gain to increase, thus resulting in the detection of unwanted (below threshold) signals. The signal from each preamp passes through a switch which selects the pair of antennas whose signal is to be processed; the other channel providing a backup in the event of a failure on the primary channel. The signal then passes through a multitap transformer which is used to set the overall gain. The gain is initially set on the vehicles and is subsequently changed in steel wheel systems as the wheels are ground down bringing the antennas closer to the signal rails.

The signal next enters the receiver where the FSK 6-bit comma-free code is separated into two parallel streams of information. Given the nature of the FSK signal, the speed code can actually be decoded by either detecting the 1's frequency and interpreting the lack of "1" as a "0" or decoding the 0's frequency and interpreting the lack of "0" as a "1". In such a manner, the two parallel streams are created. They consist of 1's clock, 1's data and 0's clock, 0's data. These two fundamental information sources are now fed to each of two microprocessors for processing. This is discussed later.

Though vital circuitry is used for gain and threshold control in the original application of the Sao Paulo system. Advancements in computer speed and memory capability make practical the use of a second receiver in this subsystem. This increases redundancy and allows checked redundant techniques to be used to establish thresholds.

Tachometer Processing Subsystem

The tachometers and associated circuitry provide the other half of the signals needed to calculate speed error. It is important to safety that the proper speed information reaches the logic. The tachometer subsystem depends on both vital and checked-redundant methods to provide its function.

The heart of the tachometer subsystem is the tachometer. Because this device is not vital, several of them must be used to provide the basis for checked-redundancy. In the Sao Paulo 108 and subsequent systems up to the new Bart equipment, four tachometers have been used. These four tachs are separated into pairs and one pair is placed on each of two separate axles. The tachs of each pair are physically arranged such that the outputs of each tach of the pair are 90-degrees out-of-phase. This provides a means for determining direction of travel.

The outputs of the four tachs are fed to a processing circuit which conditions the signals for later use. One pair of tachs is used to determine vitally the phase of the tachs and the presence of a tach signal. These vital determinations are used as part of the tach integrity indication. This vital signal must be present for the vehicle to move or continue moving. In order to allow a car to move, this signal must be created artificially until the real tachometers create an output. The artificial creation of this signal is vitally accomplished by the Startup Timer circuit.

For determination of speed error, the conditioned signals from one pair of tachs is fed to one microprocessor and the conditioned signals from the other pair of tachs is fed to the other microprocessor. Within the hardware of each microprocessor, the tachs are non-vitally checked for phase and a wheel wear calibration is accomplished for use in steel wheel systems. In the next section, we will discuss the checked-redundancy that occurs for these signals between the two microprocessors.

Again for the new more powerful microprocessors, it is possible to explore using two signal processing pathways. This allows the elimination of vital components for phase and dynamic checks and substitutes checked-redundancy across two computers.

Speed Error Generation Subsystem

The portion of the Westinghouse ATP designs which perform the speed error generation consists of vital and non-vital hardware and checked-redundant use of microprocessors. Primarily, the hardware consists of two computers and their associated I/O boards and memory circuits. In addition, a Vital Interlock circuit compares the outputs of the two computers and provide a vital enable signal.

As explained before, it is the primary function of each microprocessor to convert the tach and speed code information it receives into a speed error signal. As a secondary function, each microprocessor can be used to provide status signals as to its own well-being and to read the status signals and outputs of the other microprocessor to determine its well being. The crosschecking is the basis of the use of checked-redundancy for this system.

In performing the function outlined above, each microprocessor can use different schemes so as to avoid common failures or it can employ the same scheme if the failure modes are well thought out. Along the same lines, the Vital Interlock circuitry uses complementary inputs from each microprocessor to avoid the hardware pitfalls of common circuit implementation.

Except for the differences in the specific performance of the software functions, the techniques used by each are very similar. Since each microprocessor has both the 1's and 0's speed code data available to it, the decoding of the data can be done separately and compared.

This provides a means to compare within each microprocessor the results of two separate decodings of the same speed code; thus enhancing the checked redundancy. If the comparison of the 1's and 0's speed codes show a difference between them or if there is a difference between the presently decoded speed code and that which has been read a given number of past values before, then confusion-zone logic is executed. The confusion-zone logic normally allows the system to account for the transition from one code zone to another on the track. When a confusion-zone is detected, timers are started within the software which continue to count until a proper number of identical valid speed codes are received or the timers count out and a zero speed command is issued.

Once a valid speed command is determined, the actual speed is subtracted to arrive at the speed error. This error is enhanced by the software to provide higher resolution at the lower speed errors. In addition, a watch-dog timer output bit is used to ensure the speed decoding and speed error routines are being executed. Each time the software passes through the correct routines, this bit is toggled. A charge pump circuit converts this signal into an enable for some vital circuitry.

Each computer outputs a digital (8-bit) version of the speed error. This is taken by the Vital Interlock circuitry and converted to an analog signal. The analog versions of speed error are compared for balance and for magnitude by vital circuitry. If either speed error is too great or if the difference between speed errors is too great, zero speed is requested. In addition, the analog version of each speed error is fed to the other computer as a crosscheck. If within software, it is determined that the magnitude or balance is incorrect, then the software can declare an overspeed and stop the train.

Since implementing the first microprocessor control of safety functions into Sao Paulo 108 equipment, serial link hardware has become mature. This hardware provides a convenient way to send data from one computer to another. By using this, crosschecks on many functions can be performed. Among these additional crosschecks can be the decoded speed of the other computer and the decoded speed code. This opens the door to many additional checked-redundancy applications.

Vital Interface Subsystem

This system combines the vital outputs created by the tach integrity, speed error, overspeed balance and watch-dog timer processes. These signals are combined logically so that a loss of any of them results in a zero speed request. The circuits are implemented vitally using charge pumps, fail-safe gates and fail-safe relays. In addition, the signal power is amplified so as to be compatible with the circuits which must be driven. Basically this area continues to be done vitally in all our systems.

Propulsion/Brake Interface Subsystem

This subsystem is the final interface between the Automatic Train Control (ATC) equipment and the propulsion and braking subsystems. Traditionally, this has consisted of hardware to provide a current signal which indicates when power or brake is required. Another current signal indicates how much propulsion or braking is being requested. The hardware for this subsystem is non-vital. The safety of the system is dependant on the Vital Interface Subsystem removing power from the Propulsion/Brake Interface circuitry and disconnecting it from influence on the rest of the vehicle.

Use of Checked-Redundancy in Software

The power of software in a checked-redundant system is its ability to provide ways to satisfy the guideline that safety-related failures in the redundant system must be detected. By simply supplying the microprocessor with as many inputs from its environment as can be gotten, a whole world of logical tests and conclusions can be reached concerning the health of the system.

The major problem with software is that because of its power, programs can tend to get very complex. The more complex a program is the harder it is to test all the functions and combinations of functions which it was designed to perform. Thus, a program is likely to have some percentage of errors which were undetected in the qualification tests. To minimize this, certain basic disciplines must be adhered to in creating software. First, a top-down approach will structure the designers' view of the whole system. Second, the number of branches must be minimized to avoid complexity and thus ease program verification. Third, the programmer must use liberal, clear comments. These provide both feedback to the designer to prompt any review of what is being done and provide an easy means for someone else to understand the software.

Assuming that the software is error-free and its configuration is tightly controlled, there are still many possible execution errors which may occur due to hardware failures. It is because of these hardware failures that many software checks must be written.

Essentially, all the software checks can be combined into three areas:

1. Checking the processor environment.
2. Checking external equipment failures.
3. Providing redundancy.

The key to deciding what checks are necessary is the failure rate of components and what percentage of those failures can be considered safety related. Within the software industry certain checks are being developed as standards, checksum and instruction set tests are among them.

Expanding on the three areas of software checks we get the following list:

I. Checking the processor environment.

1. RAM Integrity Test

   Basically this checks to see if the software can write and read accurately from each position in the RAM.

2. Checksum (ROM check)

   This is considered the best single test to have. It provides some assurance that the fixed software has not changed by summing the bits in a correct program and comparing that sum to a sum check performed during operation. There are a variety of methods to do this.

3. Instruction Set Test

   This checks to see if each instruction can be performed by the computer. Not all instructions may need to be checked (or can be checked). This test has not been done on any of our systems.

4. Stack Pointer Overflow

   This test checks for multiple interrupts, illegal loops and software bugs.

5. Check In - Check Out

   Also protects against multiple interrupts and software bugs. This is a manner of writing the software so that the program exits properly from each routine it enters into.

II. Checking External Equipment Failures

1. Tachometer Checks.

   These checks can cover things such as tach pressure, tach reasonableness and tach comparisons.

2. Accelerometer Checks

   Checks for scaling changes.

3. Clock and Timer Integrity

   This has not been done on any system of ours as yet. Essentially this check would need an independant clock to compare with the timing of the CPU clock. Since there are upper and lower clock limits for proper CPU operation, a check to make sure we are operating within those limits could be useful.

4. Miscellaneous Equipment

The status of many pieces of equipment can be brought into the computer for later manipulation within the logic.

III. Providing Redundancy

1. Using two different programmers for safety software.

This is not recommended presently though in the past it was our stated method. This is due to a belief that a thorough analysis of the program will uncover faults and common failures. These can then be handled specifically.

2. Double Storage of Critical Variables

Provides a way to catch software bugs, problems with address lines and RAM's. Can be run each time a variable is used and thus covers potential failures more quickly than the RAM Integrity test.

3. Double Timers

Same as 2. above.

4. Crosschecks

Using two or more computers performing the same function, each can check the others results for key calculations, inputs and outputs. This becomes the powerful aspect of using microprocessors.

Future Trends for Use of Checked-Redundancy

The present trends in microprocessor hardware and software will have a large impact on expanding the use of checked-redundancy. The demands for smaller but more powerful and versatile designs is being stirred and satisfied by the ever increasing availability of memory and microprocessor sophistication.

Within the Westinghouse Vehicle designs, several new steps have been taken to keep pace with these trends. For the hardware being designed for Bart, 16-bit microprocessors will be used instead of the 8-bit used in all the past microprocessor designs. This decision is in line with the ever increasing use of software to perform tasks originally associated with hardware.

Also with respect to hardware, three microprocessors will be used in a configuration where any two are sufficient to operate the vehicle safely. This provides a greatly expanded availability for the train since failure downtime can be lessened. It also allows all three computers to check on each other when all are powered.

The other area of major change is in software utilization. High-level languages are being explored for use in safety settings. At the present, the tight control that assembly language gives with regard to placement of stored numbers within memory gives this language the edge. With the increased memory and speed, the use of built-in test functions and fault isolation tests (BIT/FIT) is becoming an integral part of our designs.

It is easily seen that technology and the needs of the transit industry are pushing to further sophistication in an area where safety is of primary concern. The tool to use in this environment is checked-redundant microprocessors.

Bibliography

1. Summary Report on Limited Safety Study of the On-board Automatic Train Protection Equipment for the New Metro Sao Paulo Cars, Battelle Columbus Laboratories, July 31, 1980.

FAILSAFE MICROPROCESSOR INTERLOCKING WITH SAFETY ASSURANCE LOGIC™ —ESTABLISHING A VITAL BENCHMARK—

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Summary

A new generation of vital wayside interlocking logic is being implemented electronically with failsafe microprocessor-based systems. The General Railway Signal vital processor interlocking (VPI) system is based on the principles of Safety Assurance Logic, a philosophy developed by GRS in 1975 and applied to several commercially available products in which vital processes are microprocessor-controlled. The fail-safety of the VPI system is based on an extension of these principles. The VPI system is essentially a vital Boolean logic processor, enabling the functional logic of the interlocking to be expressed as a closed set of primordially safe Boolean expressions. The expression set may be constructed as a direct representation of conventional relay logic, using existing nomenclature and design principles. A computer-aided assembly package allows interactive simulation to aid in designing the functional logic, while syntax cross-checking features report nomenclature discrepancies. Vital input and output hardware assures failsafe interfacing with wayside appliances. Vital time delays are implemented internally and may be used as parameter values in the expression set. Non-vital inputs and outputs include emulation of code-system format.

What Is VPI?

The VPI system replaces conventional, failsafe, wayside relay interlocking logic with a vital microprocessor-based system using vital, solid-state input and output circuits. The word "vital" as used throughout this paper means "a characteristic of a device or process upon which the safety of the system relies."

The core of the VPI system is a vital Boolean logic processor. Since the logical functions inherent in a railroad interlocking can be reduced to a closed set of Boolean expressions, a general purpose Boolean processor, which evaluates those expressions vitally, is an efficient vehicle for interlocking control. It also offers the advantage of being able to implement the interlocking logic using expressions that are a direct representation of existing relay logic designs, designs that have become standards for individual railroads by proving themselves safe and reliable over the past 50 years.

The states of inputs from the field (switch position, track occupancy, signal status, and line circuit inputs) are vitally sensed via solid-state input circuits. These input states, once internally encoded, are used as parameter values in the Boolean expression set.

Vital solid-state output circuits are used to position switches, set signal aspects and energize relays and line circuits in accordance with the interlocking logic rules. The solid-state output circuits are designed to provide vital assurance that any system failure, which attempts to issue an improper permissive output, will be immediately detected and power to the driven output device will be immediately disabled.

The states of the vital outputs are determined by evaluating the set of Boolean expressions describing proper interlocking operation. The expression set should not only provide for efficient operation of the interlocking, but must be "primordially safe." The term "primordially safe" means that if the Boolean expression set is evaluated correctly and without failure, safe operation of the interlocking will result. The expression set is designed by the signal engineer or application engineer to satisfy the individual railroad's safety standards and operating procedures.

The VPI system is capable of generating any number of vital time delays. These time delays are identical to those generated by conventional motor-driven timers or vital solid-state timers. The time delays may be switch-settable, permanently programmed or both. The range of each vital time delay is from 0 to 59 minutes, 59 seconds, in one-second increments. These time delays are accessed, as needed, by the Boolean expression set embodying the interlocking logic rules.

Emulates Non Vital Code System

The VPI system also is capable of non-vital code system emulation. Centralized traffic control commands sent via the code lines are inserted directly into the system as expression parameters. Indication messages, which can represent the states of any vital input, output or expression parameter, are internally constructed and then delivered to the non-vital code system in the appropriate code format.

Non-vital parallel inputs can be accepted as expression parameter values (from local emergency control panels, for example). Likewise, non-vital parallel outputs may be used to illuminate local emergency control panel lamps, maintenance procedure indications, etc.

Vital emergency-working functions can be designed directly into the interlocking logic expression set to enable maintenance personnel to block switches, lock routes, etc., via specified vital local inputs.

Communication is possible between remote VPI systems in large interlockings via vital serial communication links. This feature allows large interlocking plants to be divided into sections so that the VPI system controlling the section is in proximity to its wayside hardware. Vital data are passed between VPI systems over a standard data link, such as a simple twisted-pair.

The VPI system is modular. It is easily expanded by adding functions to the expression set and inserting additional vital input and output groups.

How VPI Works

The microprocessor-based vital Boolean logic processor core is a single-processor system that processes vital data in two diverse, independent channels. A "single-processor" system does not need more than one processor for safety assurance. Although there are a number of separate processors in the VPI system, they are required to divide the work load, rather than provide safety checks on each other. System safety is ultimately assured by a directly acceptable device. "Vital data" are data representing vital parameters that have been encoded to include unique parameter identification to ensure against possible data corruption. The two "diverse independent channels" are software channels, each of which contains data representing the state of each parameter, but encoded in diverse forms. These two forms of data representation must correspond exactly for permissive outputs to be allowed.

The VPI System Cycle

One VPI system cycle consists of sensing and encoding vital and non-vital input parameters, determining the states of the vital outputs by evaluating the entire Boolean expression set using the current values of the input parameters, and driving the vital output ports to their proper states. During the cycle, the states of the vital output ports are checked every 50 milliseconds (ms).

The states of the vital inputs are sensed by circulating a unique test word through each vital input circuit for each of the two diverse independent channels. The vital input circuit is designed so that the test word cannot be circulated through the circuit unless the input is energized. Unique code words are assigned to the TRUE and FALSE states of each input parameter for each channel. Test words are circulated serially through the input port circuit represented by that parameter. If the input is energized, the test word is returned as the TRUE code word. It is stored in an identity-sensitive location in system data memory and represents the state of the input parameter as TRUE.

An identical operation on a diverse test word is performed for the second channel. In the event that the circulated test word was corrupted or was unable to be circulated because the input was not active, the FALSE value is inserted in the memory location. Thus, the TRUE state representation of each input parameter is protected in three ways. First, the code words themselves are encoded with unique identification data, second, each value is stored in an "identity-sensitive" location in system memory, and third, different representations of the same parameter exist in each of two independent channels. Note that TRUE parameter values appear nowhere in machine-readable permanent memory.

The Boolean expression set that describes the logical operation of the interlocking contains expressions of the form:

$$X = (A*B*C) + (D*/E*F*G) + \ldots..$$

where "X" is the result, (A*B*C) is the first product term, consisting of parameters A, B, and C, and (D*/E*F*G) is the second product term, consisting of parameters D, E, F, and G. Expressions written using this format are said to be in "sum of products" form. The first product term is said to be TRUE if all of its parameters A, B, and C exist in their TRUE states. Here, the "*" symbol indicates "logical and." The second product term is said to be TRUE if parameters D, F, and G exist in their TRUE states and parameter E exists in its FALSE state. Here, the "/" symbol denotes the false state of the parameter that follows (E in this case). The expression result "X" is said to be TRUE if any of the product terms is TRUE. Thus, the "+" symbol indicates "logical or." In the event that no product term is TRUE, the expression result is FALSE.

Unlimited Product Terms

There is no practical limit to the number of product terms contained in an expression or to the number of parameters contained in any product term. The parameters in an expression may represent the states of any of the following:

- vital inputs
- non-vital inputs

- results of previous expressions (evaluated during the current system cycle)
- results of subsequent expressions (evaluated during the previous system cycle)
- the result of the current expression (evaulated during the previous system cycle)

Note that the use of expression results evaluated on the previous system cycle allows the expressions to emulate "self-latching" relay configurations.

The entire expression set exists in each of the two diverse independent channels. Parameter values used in evaluating channel 1 expressions are members of the channel 1 code word set and are located in identity-sensitive locations in channel 1 data memory, and likewise for channel 2.

An expression is evaluated by processing the parameter values for each product term. If the expression is TRUE, the result of the process is a unique code word that contains the encoded result identity. If the expression is FALSE, a default FALSE value is used. The TRUE value of any expression result does not exist in system memory. It can be constructed only by correctly evaluating the expression in which at least one of the product terms is TRUE.

After the expression set has been completely evaluated in both channels, those expression results that directly determine the states of the system's vital outputs are examined and the output circuits are driven to the corresponding states.

After the vital output states have been established, the system constructs the non-vital indication messages, which are then transmitted serially on the code system communication lines in the proper code format or transmitted in parallel on non-vital output ports.

The VPI system cycle is now complete. The duration of the cycle is one second. However, a "vital recheck" cycle occurs every 50 ms during the one-second VPI system cycle as explained below.

What Makes VPI Safe?

Safety Assurance Logic

Safety Assurance Logic is the GRS trademark for the design of failsafe processor products or systems using a single processor with two logic systems incorporated in the program. The primary logic performs the necessary task (executes interlocking logic, for example) and the Safety Assurance Logic proves that the primary task is performed correctly, or does not allow an output to be delivered. The most simple processor-based system comprises a central logic unit and the necessary devices to send inputs to it and deliver outputs from it. The vital processor-based system has, in addition, Safety Assurance Logic and design attention directed to the safety implications of its connections to other safety systems or appliances.

The primary logic is designed to be safe, but it, in itself, cannot be used as a failsafe system. Safety Assurance Logic must be added to verify that:

- the inputs to the processor are correct
- the program is executed correctly
- the program has not changed
- data tables have not changed
- inputs and variable data are current
- the outputs are correct
- the outputs have not been changed by device failures

The Safety Assurance Logic verifies the performance of the primary logic by making prescribed tests. These tests are designed to reveal any failures that could result in an incorrect output. Check words are generated, with each word conveying vital certification of one feature of vital performance. Check words do not exist in processor memory; therefore, a complete complement of check words is assurance that all vital tests were made and passed. All tests must be repeated on every processor cycle and new check words must be generated.

The "watchdog" of the system is the "vital driver." This is a processor-based device that assimilates the complement of check words in each cycle and generates a dynamic signal of an exact form and frequency. The dynamic signal is then passed through a vital analog frequency decoder, which assures that its form and frequency content are correct and generates a DC voltage which, in turn, picks a vital relay. Closure of the vital relay's front contacts provides the only source of power to the vital system outputs.

A full complement of check words enables the vital driver logic to produce its dynamic output for only a vitally-limited time. The production of the dynamic output not only verifies that every check word is correct, but also that the check words are vitally destroyed as a necessary condition for the dynamic output to exit.

In the case of the VPI system, a full complement of check words is delivered every 50 ms. The check word set enables the vital driver to produce only 50 ms of dynamic output. Unless constantly refreshed with new checkword data each 50 ms, the dynamic signal ceases and the vital relay opens its front contacts, disabling power to the vital outputs.

Numerically Integrated Safety Assurance Logic

Systems, such as VPI, differ from products, such as the GRS Microchron™ vital timer, in that the process of accommodating the unique variations associated with each application is more involved. In the case of Microchron, the unique requirements of each application are accommodated by simply setting the front-panel switches to the desired time interval. The instructions and data in the permanent processor memory are not changed. With VPI, however, each application requires its own unique set of expressions and parameters, which leads to a unique pattern of 1's and 0's in the associated microprocessor memory.

The implied need to redesign the Safety Assurance Logic for each new application has been eliminated by the development of a variation of the Safety Assurance Logic concept in which the vital check word structure is woven throughout the data. Instead of check words being built in parallel with the processing of the data to prove that the processing has occurred, the check word information is built into the data structure. The bits in each check word are made to depend upon every parameter and process upon which the permissive output depends. Any check word built from incorrect data or incorrect processing will be affected.

This variation allows all the program instructions (routines) to be designed as universally applicable to all interlockings. The application-dependent information is contained in a data base. In this way, all of the program may be written at the outset and thoroughly debugged. Once this is done, it is only necessary to create a new data base for each new application. The Safety Assurance Logic, which assures that the system performs correctly or not at all, is imbedded in the unique data base. This variation is known as "Numerically Integrated Safety Assurance Logic."

An important application of Numerically Integrated Safety Assurance Logic in the VPI system is the assurance that vital outputs are in their non-permissive states, unless specifically allowed to be permissive by TRUE expression result values in both channels. This is accomplished by executing a "vital recheck" program every 50 ms. The vital recheck program circulates unique test words through the vital "absence-of-current detector" (AOCD) circuit associated with each vital output. This vital circuit allows a test word to be circulated only if the current flowing through the output wire is zero (below a vitally established threshold that is sufficiently low so that the driven appliance will not interpret it as permissive). If test words that have been transformed into TRUE code words are returned through the AOCD, they are proof that the output is in its non-permissive state. If TRUE code words are not returned intact, the output is assumed to be in its permissive state.

A complete set of check words is then generated. If the set is correct, it provides vital assurance that only those outputs that are supposed to be on are allowed to exist in their permissive states. A correct set of check words permits the vital driver to generate 50 ms of vital dynamic output.

Another important application of Numerically Integrated Safety Assurance Logic in the VPI system is the vital erasure of variable data buffers each system cycle (one second). On completion of each system cycle, the data buffers, which contain input parameters and expression results, are vitally erased. This is necessary to assure the use of current data every cycle. In the case of expression results used as "self-latching" parameters, vital erasure assures that these results have been evaluated on the previous cycle. The vital erasure process produces a check word set that is delivered to the vital driver at the beginning of each one-second system cycle. This check word set must be correct to enable the vital driver to produce its dynamic output for each of the recheck cycles in the subsequent system cycle.

How VPI Is Applied

Application of the VPI system begins with the definition of the input and output interfaces (vital and non-vital). Vital inputs are of one type only, while there are a variety of vital output types, including single- and double-break, low-current outputs and high-current, single-break outputs for driving signal aspects. Vital inputs and outputs are available in modular groups and are inserted into the system as needed. Non-vital I/O definition includes the type of serial code system to be emulated, as well as parallel configurations.

The application engineer then produces a "primordially safe" set of Boolean expressions that logically describes the proper operation of the interlocking. These expressions may describe the interlocking operation in a manner identical to that currently used in designing vital wayside relay logic - using the same nomenclature, the same functional logic principles, and the same logical configuration.

Computer-Aided Assembly

A "computer-aided assembly" package (CAA) has been designed to assist the application engineer in configuring the system. It includes a "logic simulation" facility that enables the Boolean expression set to be exercised, simulating functional interlocking operation. Syntax-checking features in the CAA cross-check parameter and I/O names for consistency and report discrepancies. An easy-to-use editor is available for syntax correction and expression changes. The CAA documents the physical configuration of the VPI system modules and produces wiring lists to facilitate wiring to external interlocking circuits and appliances.

The CAA constructs the vital data base from the final, primordially-safe, Boolean expression set. From this memory data base, the expression set is then reconstructed using the assigned parameter nomenclature. The reconstructed expression set can then be checked against the original to assure the engineer that the VPI system's interpretation of the expression set is correct. The primordial safety of the expression set is checked in much the same way as relay logic circuits.

The "vital routine software" resident in the VPI system remains unchanged from application to application.

The VPI system has been designed to enable operation in a fully redundant mode. This optional mode allows two identical VPI systems to be connected in parallel. In the absence of any failure, both systems are fully operational. However, only one system is driving the system outputs. In the event of a failure in one system, the outputs are automatically driven by the other system, which also reports the failure to the central office via the code system. In the redundant mode, no mechanical or electrical switching of individual outputs is necessary under failure conditions. The vital outputs of both systems are simply tied together. Vital isolation of the output ports of each system prevent one system's failure from unsafely affecting the other.

User-oriented maintenance tools will enable maintenance personnel to isolate failures in the VPI system quickly. Since only the main CPU board contains application-unique hardware (in the form of the memory data base), only a small number of universal spare board types is required to put a failed system back in operation.

THE SOLID STATE INTERLOCKING

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Summary

Solid State Interlocking is an electronic replacement for the electromechanical technology used predominantly in present day railway signalling. Interlocking logic is performed centrally by microcomputers which communicate serially with lineside processors directly controlling signalling equipment through solid state power switching devices. Hardware redundancy is used to achieve the required levels of safety and availability, and the software is designed to be of general application, being data configurable to specific installations. Comprehensive diagnostic facilities are included, and the overall design package includes application data compilers and controlled area simulation facilities. A pilot installation is currently being implemented on British Rail.

Introduction

Solid State Interlocking has been developed as an electronic replacement for present day relay-based signalling technology, with the aim of providing, at a lower cost, all the operational facilities available in British Rail's most recent power signalling installations. Cost reduction is achieved through the virtual elimination of signalling relays (except those associated with track circuits), the replacement of much cabling by serial data transmission, a reduction in the size of buildings, lower maintenance costs, and a reduction in the resources required for the planning and installation of signalling schemes.

It has not been the intention to change the appearance or behaviour of the signalling system so far as the railway operators are concerned; therefore the system has been made fully compatible with present day signalling principles and operating practices and is designed to interface directly with conventional operating panels and lineside signalling equipment. The system does, however, have the flexibility to operate in conjunction with new display technologies and higher-order control systems, and to accommodate future changes in signalling principles.

The design of the Solid State Interlocking aims to satisfy the broad objectives of equipment modularity, high system availability, ease of application, good maintainability, and cost effectiveness in both small and large applications. This paper describes the structure and operation of the system, and the hardware, software and data transmission techniques used to satisfy these objectives.

System Design

The essential features of an SSI system are illustrated in Figure 1. At the control centre are located:

- One or more microcomputer interlockings, the number depending on the size and complexity of the area to be controlled;
- The control panel, which may either take the form of a VDU installation or may be a conventional signalling panel equipped with a multiplexing system giving the interlocking access to the many switches and indications;
- A maintenance terminal providing diagnostics, event logging, and certain control facilities.

At the trackside the final connection to the signals, point machines, track circuits and other lineside signalling apparatus is made through Lineside Interface Modules, which are linked to their parent interlocking by means of a duplex data highway.

In installations of a size requiring more than one interlocking a separate local data highway is provided for passing vital information from one interlocking to another. The following paragraphs describe the major elements of the system in more detail.

The Interlockings

Each interlocking is a safe, high availability information processing system consisting of the following replaceable modules:

- Two Panel Processor modules
- Three Interlocking modules
- A Diagnostic module
- Two Data Link modules.

The three Interlocking modules operate as a triply redundant system providing very high integrity with fault tolerance. The two Panel Processor modules relieve the safety interlocking of the non-vital task of servicing the control panel, and are operated in a duplex standby mode. The two Data Link modules merely act as a hardware interface between the Interlocking modules and the duplex data highways. The Diagnostic module acts as an interpreter between the SSI and the maintenance terminal, providing installation-specific diagnostic information for the maintenance terminal processor. The diagnostic processor is fully equipped to diagnose with accuracy all but the most obscure system faults.

The Interlocking and Diagnostic modules are physically identical, and themselves consist of a number of microcomputers. The main processor is a relatively large system having 60 K bytes of read only memory in which is stored a program of quite general application and a set of information unique to the specific installation, termed "geographic data". Two further processors are dedicated to servicing the two trackside data highways, encoding and decoding messages and operating the communication protocol. A fourth processor is dedicated to passing and receiving information over the data highway which links the several interlockings of a large installation.

The interlocking processors (i.e. the main processors of the interlocking modules) are the central controlling element of the system, and are responsible for the safe execution of all interlocking logic and the issuing of correct instructions to lineside equipment. They control the timing of communications within the system and also have the responsibility of supervising the redundant system of which they are part. Their general purpose program embodies the appropriate signalling principles and the rules for operating on the geographic data to produce the precise signalling controls required. The program may therefore be likened to an interpreter, and the data to a specialised high level language.

The Panel Processor modules contain a single processor having 32 K of space for read only memory, which, as in the interlockings, is occupied partly by a program embodying the rules for calculating the correct panel display and correctly interpreting panel commands, and partly by a set of data unique to the installation which defines the particular interpretation required. The two panel processor modules operate a simple redundancy management procedure which ensures that failure of one module does not degrade the performance of the system. The panel processors and the panel multiplex equipment communicate over 2.4 kbaud asynchronous links.

The Data Highway

As the trackside data highway carries safety information and is the interlocking's sole link with the area of railway it is controlling, its security and availability are vitally important. The highway is duplicated to improve availability, and is generally composed of two parts; a point-to-point link which connects the interlocking to the geographical area concerned, and a local data distribution system giving access to all the lineside equipment associated with the interlocking.

The point-to-point link may utilise any data transmission technology offering sufficient bandwidth for further levels of coding which may be required for security reasons; however, it is a natural application for optical fibre technology whose immunity from electromagnetic interference is so attractive in the railway environment.

The data distribution system has been implemented in the form of a dedicated screened twisted pair cable, over which information is transmitted in the Manchester (or Biphase) coded form which, for example, has been previously used in aerospace applications [1,2]. All messages passed over this highway have the format illustrated in Figure 2, consisting of a synchronising and timing recovery pattern, followed by address, control and status information doubly protected by a (31, 26) Cyclic Hamming Code and the Manchester coding. The data distribution system is operated at a data rate, after Manchester coding, of 20 kbaud, giving an effective range of about 10 km which may be extended by the use of repeaters. The message protocol is controlled by the central interlocking, which sequentially addresses the 63 possible lineside interface modules, whether or not they all exist, and allows time for each to reply. The nominal message interval is 8.5 ms, giving an overall system cycle time of approximately half a second, although this may vary slightly with the workload of the interlocking.

Manchester coded messages have a number of advantages in this application, including the following:

- Messages can be transmitted over a.c. coupled lines.

- Messages are secure against truncation.

- As transmission errors must occur only in specific consecutive pairs if Manchester validity is to be preserved, there is a large gain in coding security.

- Message synchronisation is simply achieved by adding a Manchester invalid pattern at the beginning.

- A high integrity processor can protect message security by forcing suspect transmissions to be Manchester invalid.

The combination of Hamming coding, Manchester coding, and the use of relatively large signal levels (i.e. energy redundancy) in a dedicated screened transmission line gives more than adequate message security, as has been confirmed by analysis of the performance of experimental data systems of this type installed in electrified territory.

Lineside Equipment

The ultimate conversion from low level serial data to and from parallel outputs and inputs at signalling equipment power levels is handled by the Lineside Interface Modules. The two types of module which have been developed so far enable the great majority of interfacing requirements to be accommodated without resort to additional interfacing relays. The two modules are a Points Module, which is designed to interface directly with Clamplock point machines, and a Signal Module, which although being designed specifically to provide an efficient interface to multi-aspect colour light signal heads, is also sufficiently general purpose in design to satisfy most other interfacing requirements. In both modules power switching is fully solid state.

A points module will control up to four machines arranged as two independent sets, with four inputs being provided for point detection and four for track circuits or other input functions. A signal module provides 8 secure outputs at 110 V ac and 6 inputs for track circuits or other input functions. Lamp current sensing and flashing aspect capability are built in.

Lineside modules set their outputs according to instructions received in messages from the interlocking and reply giving the state of their input functions and their module status. In the event of the loss of successive messages from the interlocking, due to Manchester or Hamming parity failure, or to total breakdown of both links, a lineside module will set all its outputs to a safe state. A similar procedure is adopted by the interlocking, in that loss of two successive messages from a lineside module causes the interlocking to assume that the message from the module would have indicated the most restrictive set of conditions.

SSI Maintenance Terminal

The provision of a diagnostic aid was recognised at the outset as an essential part of the overall SSI design package. The maintenance technician has therefore been provided with a printer and keyboard, linked to a dedicated processor, through which the fault status of an interlocking, its data highways, its lineside interface modules, and the lineside signalling apparatus can be determined at any time. The keyboard may be used to request specific status information or to make permitted alterations to the behaviour of the interlocking - the barring of particular routes, for example. The printer will normally be used for fault annunciation and for providing a written record of changes made to the interlocking. A tape cassette data recorder is also provided on which all changes in system state are continuously logged. One maintenance terminal has the capacity to serve up to six interlockings.

Laboratory Development System and Simulator

The laboratory simulation of SSI installations has been an essential part of the development process. For this purpose, and also to provide an essential tool for the checking of geographic data in future applications, a Controlled Area Simulator has been developed whose function is to represent fully the area of railway being controlled by the interlocking and to respond to data highway messages as if it were the lineside interface modules of a real installation. The simulator is data configurable to represent any controlled area.

Laboratory simulation during development has been based predominantly upon a fictitious layout which has been carefully chosen to give rise to a wide range of potential signalling difficulties. The layout has 52 signalled routes, 25 controlled signals, 7 automatic signals, 13 sets of points and 47 track circuits, representing about two thirds of the capacity of one SSI.

Laboratory prototypes of the central interlocking and maintenance terminal, and a fully equipped lineside equipment cubicle, are illustrated in figures 3 and 4.

Hardware Redundancy

The problem of achieving with an electronic system the level of safety provided by present day signalling technology is without doubt the most challenging of all the technical difficulties which have had to be solved. Reliability is also a problem, in that the distributed nature of relay signalling logic ensures good overall availability even though individual functions may fail from time to time. It is therefore important to ensure that an electronic system, in which many functions may be carried out in a single piece of equipment, is equally capable of providing an adequate level of availability.

In order to meet these requirements two types of redundant equipment have been evolved. For lineside use, where the equipment complexity is small and individual equipment failures cause only localised disruption to traffic, a duplication technique is used. For the central interlocking, where high availability is essential, a repairable TMR (Triple Modular Redundancy) technique has been developed. The principles involved and some of the practical difficulties involved with these techniques are described in the following sections.

Basic Redundancy Techniques

The general principles of hardware redundancy are well known. The technique of duplication essentially involves performing the desired task in two parallel subsystems and subjecting the two sets of output information to a comparison process. If "fail-safe" behaviour is required, as it clearly is in signalling applications, the comparator must enforce a predetermined safe set of output states whenever the two subsystems fail to agree, and for this reason is usually thought of as being an intrinsically safe device, implying the use of safety relays or magnetic logic.

Triple redundancy involves performing the desired task in three parallel subsystems and subjecting the three sets of output information to a voting process, with the object of enforcing the majority opinion at all times. Thus, failure of one of the three modules is masked by the system redundancy, and the system is said to be single fault tolerant. In safe applications the voting device also has to enforce a predetermined safe set of states when a majority opinion cannot be found. Again, the voting device is usually envisaged as being intrinsically safe, bringing the same disbenefits as the intrinsically safe comparator, but on a larger scale. It is worth noting that TMR is essentially a technique for providing very high system reliability for short periods, and as such has been widely applied in the aerospace industry[3]. However, in ground-based applications the TMR system is accessible for repair, and the prompt replacement of failed modules can provide very high availability over an indefinite period.

These elementary statements of principle conceal a number of design difficulties which must be resolved before effective and practical systems can be produced[4]. The following section is intended to give some insight into these difficulties and the techniques used to overcome them.

Comparison, Voting and Redundancy Management

Solutions to the comparison and voting problem have been adopted which involve making comparison and voting a software function, and providing separate hardware for enforcing module disconnection or system shut-down.

In the duplicated system comparison is achieved by giving each module independent access to the system output states, and requiring both modules to agree at all times that the outputs are correct. In the event of disagreement, the safe shut-down condition is irreversibly enforced using special "redundancy management" hardware which consists of redundant and testable means of enforcing the required output state[5].

In the TMR system each module has a redundant and testable isolation mechanism which is operable either by itself or by the other two modules acting in cooperation. Voting is effected by each module monitoring the actions of the other two and attempting to isolate from the system any module with which it disagrees. Failure to isolate such a suspect module is presumed to imply a self fault and leads to self isolation. Module isolation causes automatic reconfiguration to the safe duplicated mode, which of course has no further fault tolerance. It can be seen that the redundancy management process is itself redundant and involves no hardware external to the three modules.

Where a redundant microcomputer system controls the switching of power to external equipment, as in the lineside interface modules, it is necessary to extend the redundancy management function to the protection of power level outputs. The precise requirements vary with the application; for example, in controlling a multi-aspect signal the requirement is to supply current to one or more of the signal lamps at all times, yet means must be provided to disconnect the supply (and enforce the most restrictive aspect) should a fault develop which would cause an incorrect lamp to be lit. On the other hand, in operating a point machine, current is supplied only on infrequent occasions, and it is desirable that at all other times the vital outputs should be individually protected against the application of power due to a fault. Solutions to both of these requirements have been devised, involving the use of redundant and testable protective circuits.

Divergence and Synchronisation

The extent to which the several modules of a multiply redundant system should be synchronised is a matter of debate. Generally it is felt that total asynchronism places excessive constraints on system design and performance, while strict hardware synchronisation is inappropriate in a safe system from the point of view of independence between modules. Associated with this design decision is the phenomenon, which the authors have chosen to term "divergence", which arises when the different modules of the redundant system perceive different sets of input states, causing them to follow different and divergent program paths, eventually leading to disagreement and system shutdown. The solution to this problem involves a mutual exchange of opinions about input states and application of a suitable strategy for coping with temporary disagreement. This and other requirements for communicating between modules have led to the choice of a software synchronisation technique which normally maintains a stagger of a few microseconds between the programs running in the two or three subsystems.

Fault Detection Coverage

Clearly, voting or comparison at module outputs cannot detect a fault in a module until it has been manifested as an erroneous output state. Safe systems will generally require more extensive fault detection coverage, and the existence of inter-module links for antidivergence and synchronisation purposes enables this to be achieved by exchanging and comparing information about the modules' internal states. Self testing also has a role to play in minimising the risk of undetected faults, as does the testing of peripheral hardware and the use in redundancy management hardware of circuit elements requiring periodic refreshing. All of these techniques are used in one form or another in Solid State Interlocking to create a system with very comprehensive fault detection coverage.

Repairability

The triple redundancy system developed for the central signalling logic has been designed so that repair is simply a matter of removing the failed module and substituting a replacement. This can be achieved without disturbing the continuing correct operation of the surviving duplicated system. However, when the replacement becomes active, it has to synchronise to the existing modules and be updated with the exact current state of the system before being allowed to activate its redundancy management and output circuits, thereby restoring full triplication. The updating process itself has to be redundant in order to avoid the possibility of corrupt information being transferred. The new module is therefore updated independently by the two existing modules, and both sets of information are required to be identical.

Software Considerations

Minimising the effort required to develop, check, and subsequently modify software with safety responsibilities was recognised from the outset as a vital aspect of system design. The design therefore aims to minimise the total quantity of safety level software, to minimise its complexity, and to ensure that the same set of software is of universal application. Reflecting this aim, the various processors of the SSI central interlocking are provided with a set of software capable of providing all the necessary signalling functions irrespective of where the system is installed. As has been already explained, the resident program is in the nature of an interpreter which operates on a fixed data set which is unique to the application and defines the physical arrangement of the installation and the precise signalling controls required. The data is compiled from source information which includes the arrangement of panel controls and indications, the allocation of functions to trackside modules, and the signalling control tables. Data compilers have been written which can be run on a proprietary desk top computer.

The lineside modules are not data configurable, all necessary functional variations being selectable by external wiring options.

Software Integrity

In a safety system such as the Solid State Interlocking the software integrity requirements are of the highest order. Not only must the software be reliable in the conventional sense, but it must be shown to be correct with a very high degree of confidence.

Software integrity is a subject capable of arousing considerable controversy. One school of thought regards correct software as unattainable, and considers that safety demands the creation of independent sets of software for each module of a hardware redundant system, arguing that software design errors are thereby forced to reveal themselves as safe system failures [6]. While there is no doubt about the philosophical appeal of this argument, the approach is flawed by its inability to overcome the problem of specification errors, which are commonly the dominant cause of malfunction in complex real time systems, and by the resourcing and other practical difficulties which are created.

The Solid State Interlocking design team have taken the view that, strictly in the context of the relatively small real-time software systems involved, it is better to devote the available resources to design and validation procedures capable of generating the required degree of confidence in the correctness of the software. A great deal of attention has therefore been given to producing high quality software and documentation, and to subsequent testing and analysis. Formal methods of software design have been used which force the programmer to produce well structured programs. Careful design of program and data structures can recover some of the functional isolation which is inherent an a hard-wired system but is essentially absent in a computer. Specification is a problem, as plain language can be ambiguous and is generally lacking in precision, while formal specification languages require a great deal on intellectual effort to apply and cannot easily be understood by all the parties concerned. The development of a comprehensive specification is inevitably an iterative process.

Various formal validation techniques have been used, including equivalence analysis, structural analysis and semantic analysis [7]. Testing with carefully chosen data, while not in itself sufficient to demonstrate software correctness, has proved to be a more powerful way of finding errors than conventional wisdom admits.

System Trials

Solid State Interlocking is currently being installed at Leamington Spa on the London Midland Region of British Rail. The pilot installation extends to about 15 route km, and is comparable in terms of the number of routes and functions with the laboratory experimental layout mentioned earlier. A period of off-line operation is scheduled to begin in the summer of 1984, during which the system will be exercised in situ using an extension of the controlled area simulator to provide input stimuli to lineside interface modules, and its performance will be monitored by comprehensive data logging equipment. Service operation is due to begin in the spring of 1985. Assuming the success of these trials, Solid State Interlocking will become the standard technology for future main line signalling schemes on BR.

References

1. Gross, J.P., 'Data bus techniques for digital avionics', Proc. IEEE National Aerospace Electronics Conf., New York, USA, 1973.
2. Balliet, L., and Hockenburger, R.: 'A wideband data distribution system.', IEEE International Convention and Exposition, New York, USA, 1973.
3. Avizienis, A.: 'The STAR computer: an investigation into the theory and practice of fault-tolerant computer design', IEEE Trans. Comput., vol C-20, pp1312-1321, 1971.
4. Cribbens, A.H., 'Advanced techniques for microprocessor systems', pp72-76, Ed. F.K. Hanna, Peter Peregrinus Ltd., London.
5. Cribbens, A.H., Newing, D.H., and Ryland, H.A.: 'The microprocessor as a railway control system component', Microprocessors, vol.1, pp 447-47, 1976.
6. Von Linde, O.: 'Computers can now perform vital functions safely', Railway Gazette International, pp 1004-7, Nov. 1979.
7. Short, R.C.: 'Software validation for a railway signalling system', IFAC Conf. Safety of Computer Control Systems, Ed. J.A. Baylis, pp 183-189, 1983.

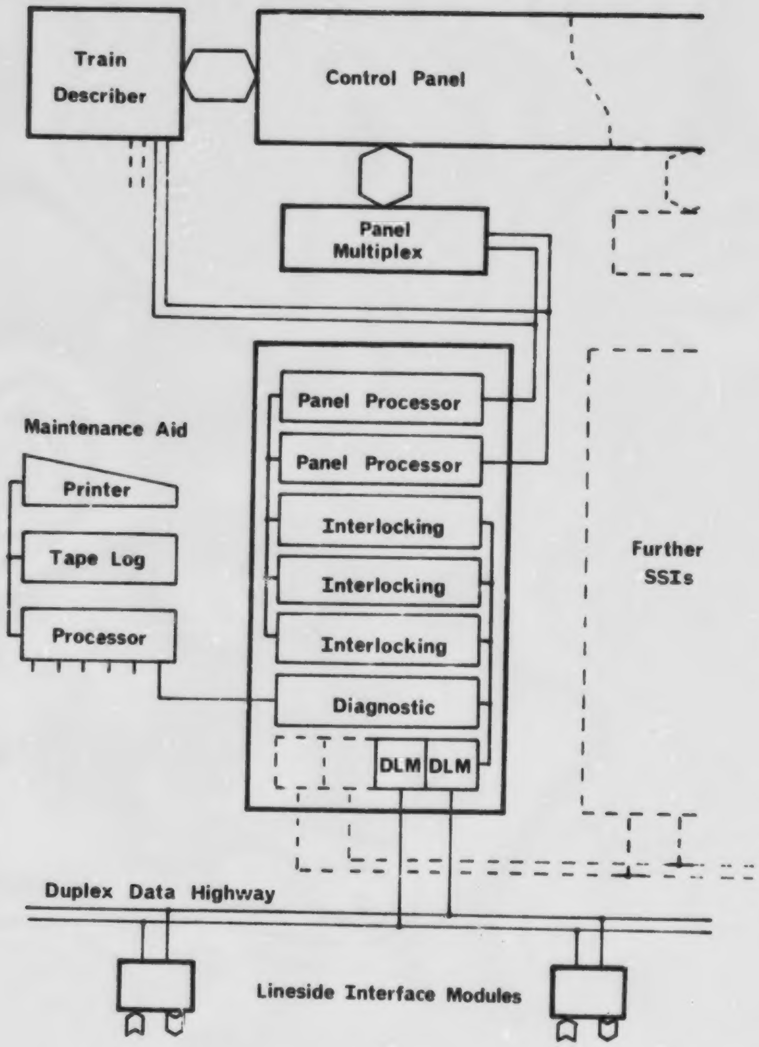
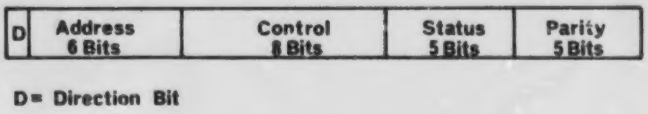
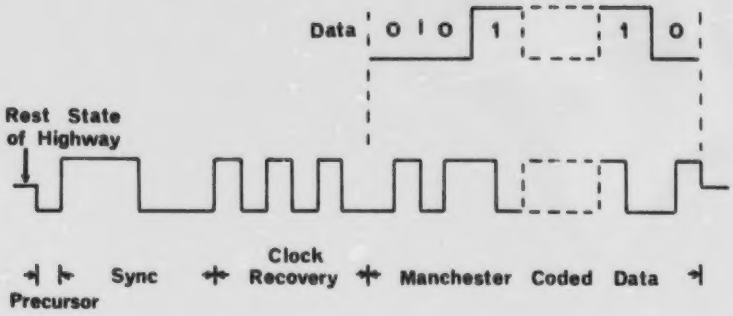

Train
Describer
Control Panel
Panel
Multiplex
Maintenance Aid
Printer
Tape Log
Processor
Panel Processor
Panel Processor
Interlocking
Interlocking
Interlocking
Diagnostic
DLM
DLM
Further
SSIs
Duplex Data Highway
Lineside Interface Modules

Figure 1. Essential features of a Solid State Interlocking installation.


D
Address
6 Bits
Control
8 Bits
Status
5 Bits
Parity
5 Bits
D= Direction Bit

(a) Data Format


Data
0
0
1
1
0
Rest State
of Highway
Precursor
Sync
Clock
Recovery
Manchester Coded Data

(b) Manchester Coded Baseband Message

Figure 2. Data highway message format.

Figure 3. Laboratory prototype interlocking and maintenance terminal.

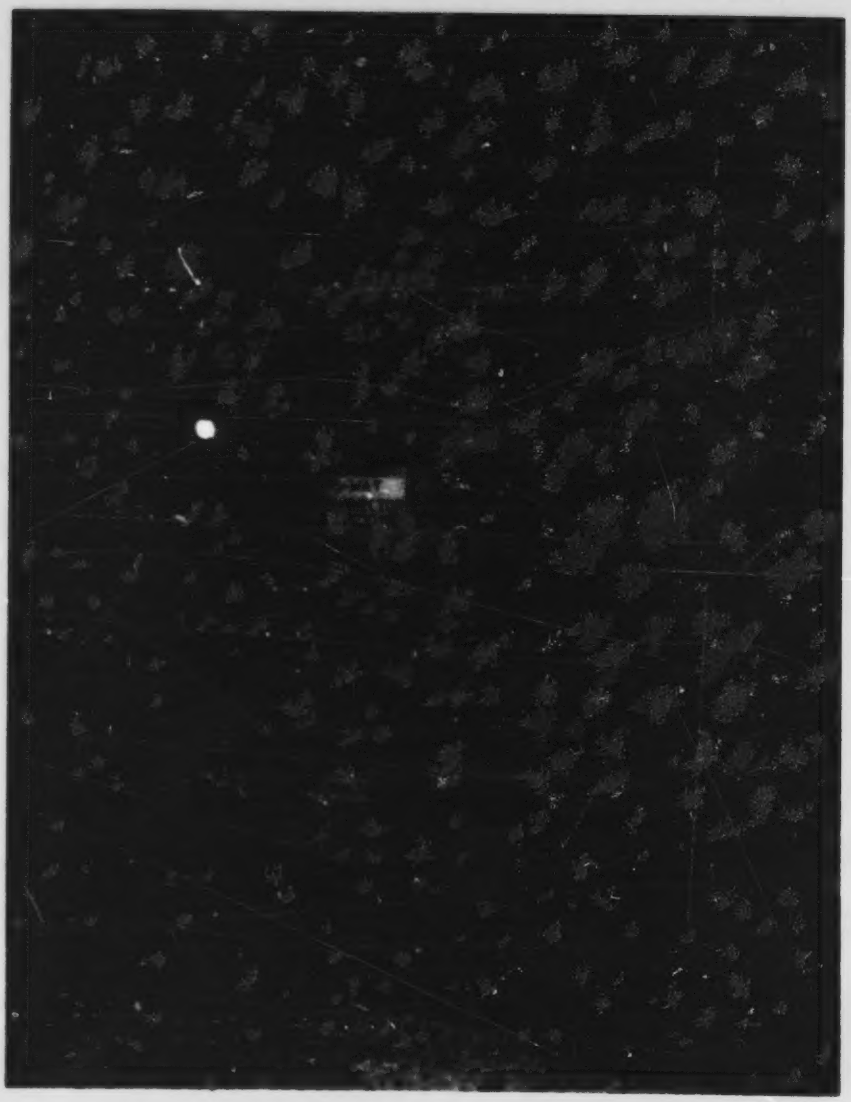


Figure 4. A typical lineside equipment cubicle. (Court[illegible] of GEC-General Signal Ltd.).

STEPS OF DEVELOPMENT UNTIL MICROCOMPUTER-INTERLOCKING

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Summary

Interlockings, even those of the most up-to-date constructions, continue to operate in their logic and control units by means of a long-established electromechanical component, the relay. Over the decades, relay technique has been continuously refined so that the present modern all-relay interlockings have reached a stage whereby both technically and operationally, there leaves little-to-be desired.

Even so, with a combination of the latest technologies, i.e. microcomputers with the optical fibre cable, the interlockings can be further optimized. Already the first systems of the new Siemens-designed interlocking generation, which is based on the section-controlled principle using the SIMIS, fail-safe-microcomputer system, are installed and are in "real" operation (industrial railway) or operating on a trial basis (Berlin underground BVG). A system for a long-distance railway, i.e. for the Dutch Railway Authorities, is in the process of construction.

General

The modern technology of electronics can be applied to many areas of activity. For 25 years, we have investigated which branches of railway signalling technology are adaptable to electronics. Some of our present equipment would have been totally unrealisable without the switching speeds of electronics, e.g. automatic train control or computers in operational control centres. For other types of equipment, such as that for hump yard control in marshalling yards. It is cheaper to apply electronics than to use relay techniques and here we have already changed over to electronic equipment.

Due to the particular characteristics of interlocking systems, interlockings are still based on the use of specific relays. I would like to mention the most important of them:

- The logic of an interlocking is relatively simple, the operational speed is low and a large storage is not required. Thus the advantages which electronic components have over relays are not utilized.
- The central part of an interlocking has numerous interfaces to other parts of the system. These include, at track level, signals and points and in the control panels, lamps and buttons. In order to adapt the energy levels and to avoid interference, these interfaces are rather expensive even when using relay technology. With the application of electronics this would not be reduced.
- An interlocking must operate fail-safe. A signal relay, on account of its construction, possesses most of the requirements for a fail-safe operation. A normal electronic component has a random defect characteristic.

Steps of Development

As electronic components are continuously becoming cheaper we can assume that it is only a matter of time before electronic interlockings will compete with present-day technology. For a number of years we have investigated every step which electronic technology has taken with a view to adaptability for fail-safe systems. In order not to base our consideration purely on theory, we have already built prototypes.

At the start of the sixties, a first fail-safe circuitry was developed in our laboratories using discrete components, such as magnetic cores, transistors and resistors. With this technique we were able to realize for the first time continuous train control which has been successfully applied in numerous systems. An experiment was conducted in order to apply this technique to an interlocking using the Spoorplan concept. However, this failed for purely economical reasons.

As the intergration of several electronic components into a single unit advanced, an inte grated fail-safe technique called URTL, was conceived. URTL stands for a supervised resistor - transistor logic. Each gate and flip-flop is doubled in this system whereby using a dynamic pulse control one alternates between the parallel stages.

The success of the URTL technology was restricted on the one hand owing to the high costs of the integrated units and on the other hand owing to the necessary basic expenditure for the pulse generation, the supervisory system and so on, which is of importance especially in smaller systems.

As a result of mass integration, a solution to this problem was seen to lie in the development of a specific unit whereby several hundred URTL units could be integrated onto a silicon chip of approximately 10 square millimeter.

But since this development would have been purely for systems requiring safe functions, it would have resulted in a relatively small production of a large variety of units. Thus the price level, which one achieves as a result of mass production, again was not obtainable.

Simultaneously, semi-conductor manufacturers were developing the first highly integrated circuits, which were the forerunners of the present-day microprocessor. Today the microprocessor has established itself as a very important tool for control systems. We believe that by using this universal element, economical solutions will be achievable also in the field of railway signalling.

At an early stage we began to consider the different applications for the microprocessor. As a result, the MES 80 microcomputer system for railway signalling, as well as the SIMIS safe version, has been developed.

Fail-Safe Microcomputer system

Modules of the standardized microcomputer system for railway signalling, the MES 80 are used for the SIMIS fail-safe microcomputer system. The arrangement and method of operation of the two MES 80 microcomputers are such that the signalling equipment can be guaranteed to operate in a fail-safe way.

The fail-safe signalling of the SIMIS microcomputer system is based on the certain detection of processing errors. On detecting an error, further processing is inhibited and the control output (interface to the process unit) are blocked. For this reason the fail-safe SIMIS microcomputer system consists of (figure 1):

a) two MES 80 microcomputer systems which are of the same design, have identical programs and are supplied with the same data, and

b) a fail-safe signalling hardware operating system.

The operating system supplies the two microcomputers with the necessary control signals and thereby provides a processing operation which issynchronous but at the same time independent. The operating system detects a deviation of one microcomputer's processing from that of the other microcomputer and then inhibits further processing.

The SIMIS operating system consists of the SIMIS pulse generator and the comparator modules. The comparator modules comprise comparing elements for the signals of the address bus, data bus and outputs of the two microcomputers.

By means of the SIMIS fail-safe microcomputer system, we have a safe technique which can be universally applied and which is able to perform all the processing tasks coming within the framework of an interlocking.

Structure of Interlocking

Our investigations have indicated that a system using microcomputer technology and structured with a minimum number of modules presents the most economical and reliable solution.

Figure 2 shows the basic structure of such an interlocking. The processing level consists of a number of microcomputer systems which contain the interlocking logic and are connected via input/output bus with the control panel of the operator. As in present interlockings the microcomputer systems are connected via control and supervision elements to the trackside elements, for instance, points and various types of signals. The mentioned interface poses a technological problem since it is not possible to control the external elements by means of the output level of our control and supervision units. The trackside elements have a far higher energy requirement and are subject to extreme electrical interference. If the control and supervision units are now replaced with microcomputers instead of relays as in the present interlockings, much has to be done in order to compensate for the difference in potential between the electronics and the relays.

New solutions have to be sought in order to reduce the costs of the interface. A new transmission medium, the so-called optical fibre, could help to achieve this, because this method allows transmission of information on a low energy level.

In addition to this advantage, the interference immunity of the transmission medium is of great importance. Thus, on the one hand, this optical transmission technique allows us to obtain and transmit more information from the process, and on the other hand, operation is independent of external influence, naturally within the physical limits of the fibre material.

In the case of the electronic interlocking, signals are controlled and monitored by means of optical waveguides.

Figure 3 shows the operating principle of signal control and monitoring equipment.

Let us return to the modularly structured multimicrocomputer system (figure 2).
At least two variations are possible. For one variation, the microcomputer system can control and supervise several similar elements of the external lay-out. In this case, as presented in figure 4, each logical unit of the interlocking would be responsible for say 25 points or crossing or a corresponding number of signals. Thus we have created the term "Element-Type Computer Interlocking". A particular interlocking has to have at least as many such element type computers as there are differing element types.

We have decided upon the second variation which we have called "Section Computer Interlocking".

Section Computer Interlocking

In the case of a section-controlled interlocking, the track layout of a station (or several stations) is divided into several interlocking sections if possible of equal size. A processing unit - called section-computer - is assigned to each of the sections. Thereby it is important to devide the track site into longitudinal sections (parallel to the main direction of traffic) with throughroutes. By this means a higher availability is attained than that of a division which crosses traffic direction. The basic structure of the "Section Computer Interlocking" is shown in figure 5.

The interface of the section-controlled interlocking which for staff is a keyboard, a VDU, a printer and corresponding processing units (computer for inputs, indications, and interfaces). The control and supervision of the outside system (signals, point machines, level crossings, track vacancy indications) takes place by means of a control and supervisory computer level. Whilst the first-mentioned computers have access to all section computers, the control and supervisory computers are assigned to certain section computers.

The section computers contain the interlocking logic. The processing programs for all occuring element types are stored, independent of the configuration in the station, in each section computer. The station-specific data for the elements, the distribution of the elements to the section computers, the relationships between neighbouring elements on the track site and the element designations are transferred during a loading process to the section computers where they are stored. However, section computers can also be individually loaded. The actual state of the outside elements is given by the control computers.

Such an interlocking system has the advantage of a higher availability of the complete system as well as a lower basic expenditure, resulting in a more economical solution for smaller stations.

It is evident that the software must be structured into clear-cut modules, which are essential for safety approval.

The implementation of the Electronic Interlocking System

Already several interlockings based on the section computer principle, have been installed or are in the process of being installed.

For the Berlin Transport Authorities (BVG), an electronic interlocking in Uhlandstraße Underground Station has been intrial operation since the middle of 1982. A corresponding interlocking for an industrial railway has been in "real operation" since February 1983. At the present time, we are installing an electronic interlocking in Hilversum station for the Dutch Railway Authorities.

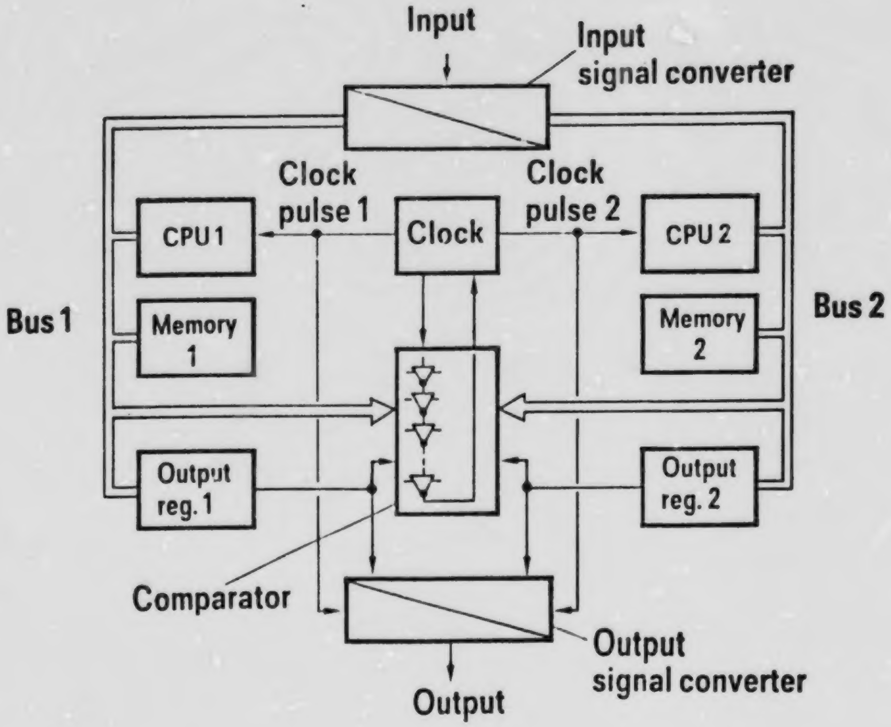
Input
Input signal converter
Clock pulse 1
Clock pulse 2
CPU 1
Clock
CPU 2
Bus 1
Memory 1
Memory 2
Bus 2
Output reg. 1
Output reg. 2
Comparator
Output signal converter
Output

Fig.1 SIMIS fail safe microcomputer system

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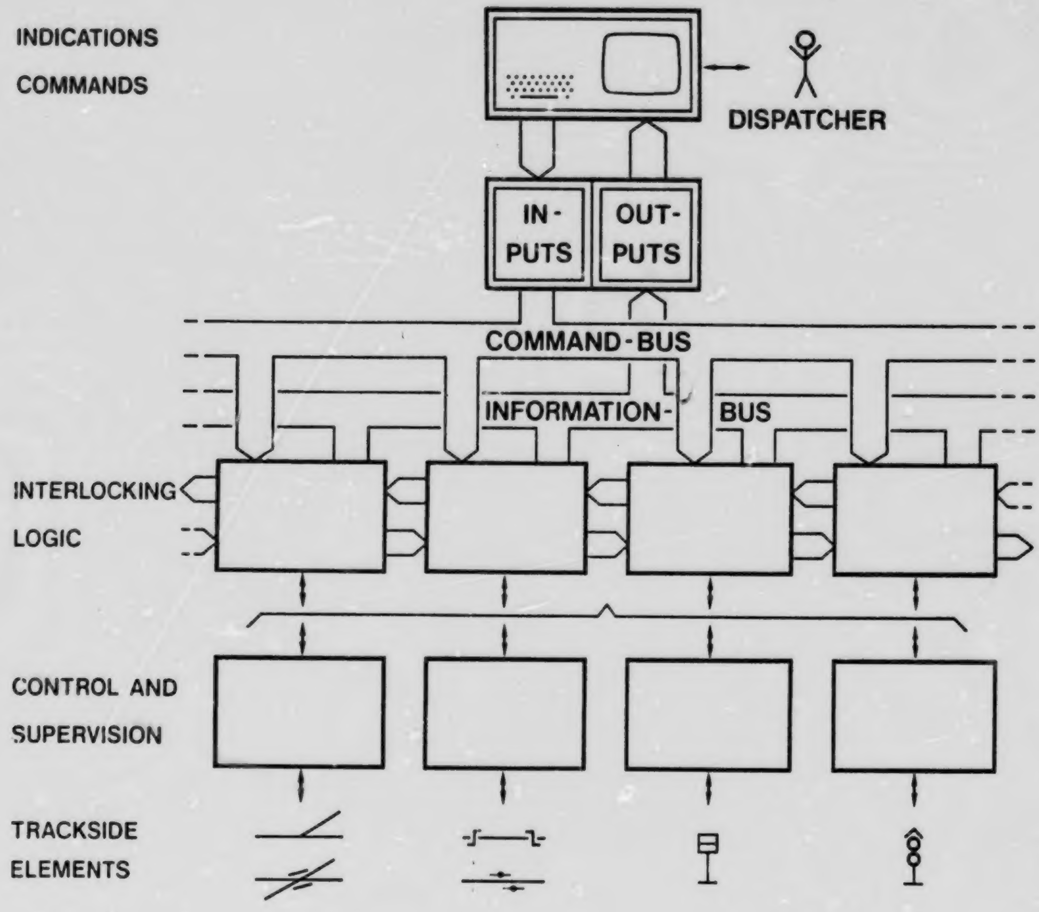
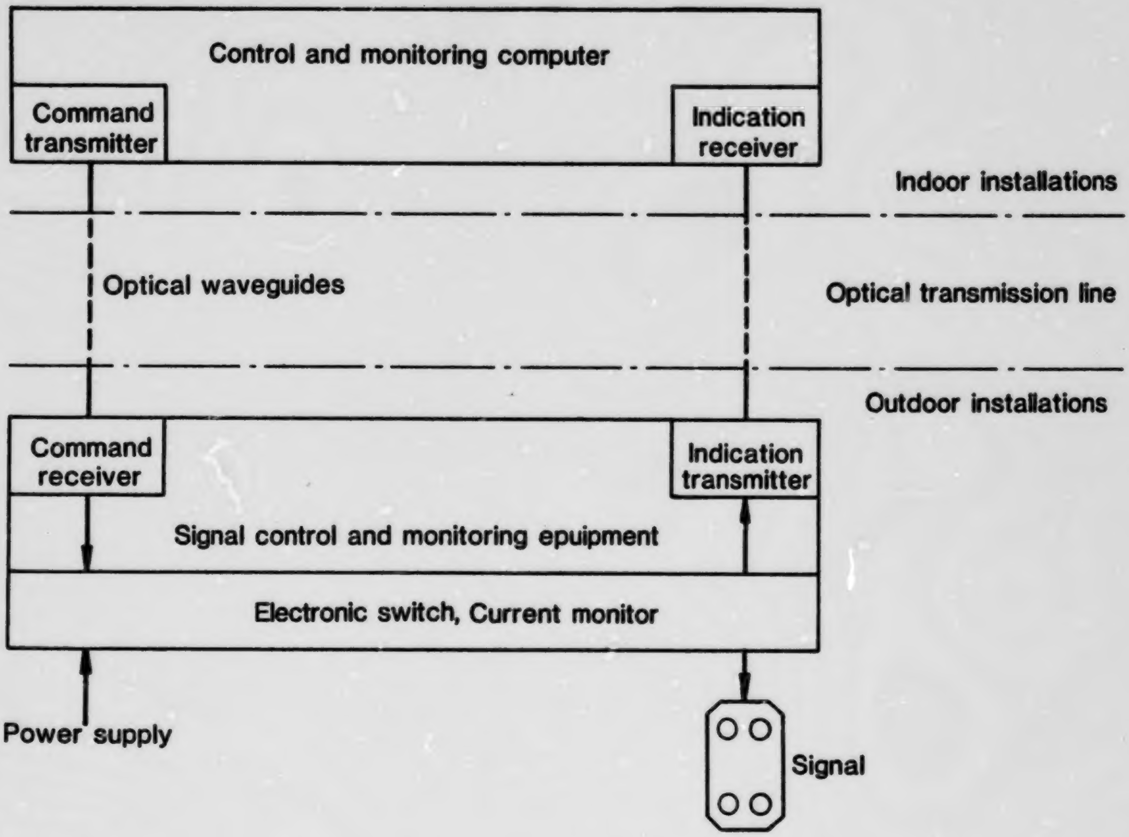

INDICATIONS
COMMANDS
DISPATCHER
IN-PUTS
OUT-PUTS
COMMAND-BUS
INFORMATION-BUS
INTERLOCKING LOGIC
CONTROL AND SUPERVISION
TRACKSIDE ELEMENTS

Fig.2 Microcomputer interlocking,components



Control and monitoring computer
Command transmitter
Indication receiver
Indoor installations
Optical waveguides
Optical transmission line
Outdoor installations
Command receiver
Indication transmitter
Signal control and monitoring epuipment
Electronic switch, Current monitor
Power supply
Signal

Fig.3 Operating principle of the signal control and monitoring equipment

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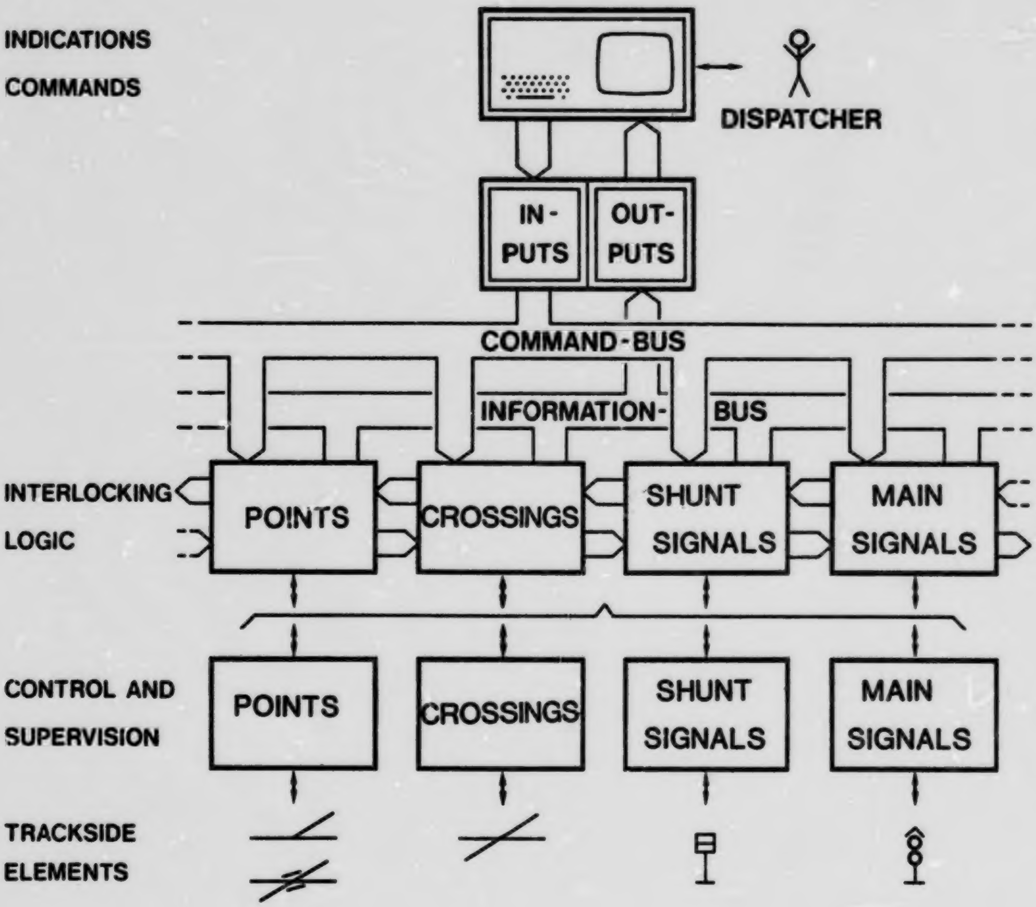
INDICATIONS
COMMANDS
DISPATCHER
IN-PUTS
OUT-PUTS
COMMAND-BUS
INFORMATION-BUS
INTERLOCKING LOGIC
POINTS
CROSSINGS
SHUNT SIGNALS
MAIN SIGNALS
CONTROL AND SUPERVISION
POINTS
CROSSINGS
SHUNT SIGNALS
MAIN SIGNALS
TRACKSIDE ELEMENTS

Fig. 4 ELEMENT–TYP–COMPUTER INTERLOCKING

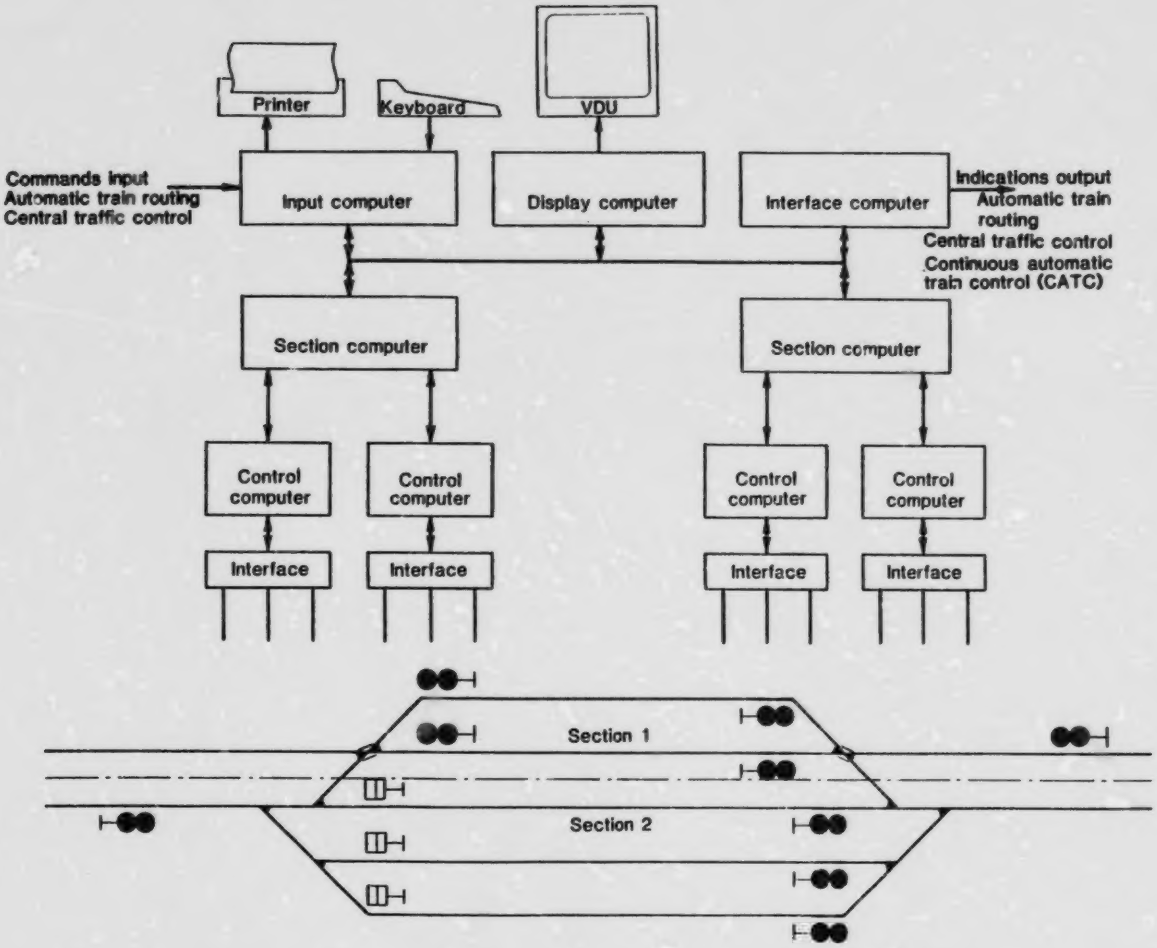
Printer
Keyboard
VDU
Commands input
Automatic train routing
Central traffic control
Input computer
Display computer
Interface computer
Indications output
Automatic train routing
Central traffic control
Continuous automatic train control (CATC)
Section computer
Section computer
Control computer
Control computer
Control computer
Control computer
Interface
Interface
Interface
Interface
Section 1
Section 2

Fig.5 SECTION- COMPUTER INTERLOCKING

OPTICAL FIBER TRANSMISSION SYSTEM FOR APPLICATION IN RAILWAY VEHICLES

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Hajime Ochiai, Kazuyoshi Ohshima
Mitsubishi Electric Corporation
Japan

1.Introduction

Transmission system making use of fiber optics have many exellent characteristics suittable for railway vehicles: for example the ability to reduce susceptibility to noise from electromagnetic or radio-frequency interference, reduction in vehicle weight, expantion of transmission information having come to be a standstill in conventional method by number of passing wires, etc. Paying attention to the above-mentioned characteristics, Mitsubishi Electric Corp. have developed the following systems to apply the optical fiber transmission system to railway vehicles.

(1)Information transmission between on-board control system of magnetic levitation type railways of Japanese National Railways.

(2)Information transmission between chopper control units of light cars of Hiroshima City cars

(3)Information transmissin system in assumption of electric trains of numbers of cars.

(4)Control information transmission unit for use of subwaycars of Ginza-Marunouchi Line of Teito Rapid Transit Auhority .

The following papers outline the above-mentioned descriptions.

2. Investigation of Component:

For application of the optical fiber transmission system to railway vehicles, it is necessary to construct a system in full consideration of the characteristics as railway vehicles. Reference is made to the result of the investigation of principal constituting elements of the optical fiber transmittion system.

2.1 Selection of Optical Fiber:

The optical fiber cord povides such kinds as multimode step-index, graded-index, single mode step-index. More over, each type has some kinds of type differ in core diameter and clad diameter. In consideration of application of optical fiber to railway vehicles, it differs in comparison with general optical fiber transmission circuit with short line distance between stations, existence of great number of connections where jumper connector, etc. Comparison of each fiber taking account of such characteristics is shown in Table 1.
As a result of overall judgmint of them, it has been decided to take up the multimode step-index of core diameter being 100μ m and clad diameter being 150μ m.

2.2 Selection of Sheath of Optical Fiber Cable:

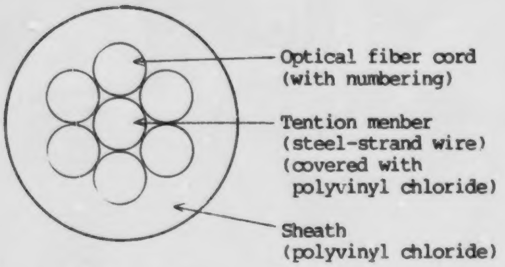
As conventional sheath materials of electric wires for use of railway vehicles, polychloroprene rubber and polyvinyl chloride have much been used.
In comparison of mechanical strengh,manufacturing methcd, hardly combustion, and economical efficiency in both of them, it has been decided for the opical fiber cable for use of railway vehicles to take up polyvinyl chloride of actual records as the sheath material.

2.3 Construction of optical fiber cable:

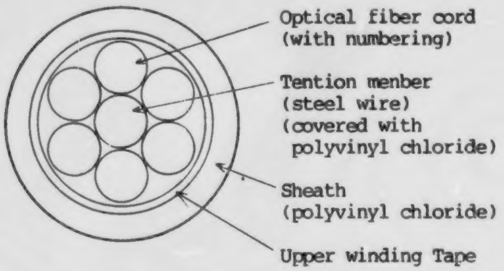
The number of optical fiber line in the cable has adopted six-core one at the last stage.
This has been considered in such manner that, with two cores taken as a double loop for control information transmission for example, one for

TABLE 1
Comparison of MultiMode Step-Index with Graded-Index for Application in Railway Vehicle

Item	Step-index	Graded-index	note
Transmission band width	20~40 MHz·km	>200 MHz·km	It is sufficienteven by a step-index fiber because transmission area is restrictive.
Transmission loss	2~10 dB/km	2.5~10 dB/km	It matters little what transmission loss of fibers for short route between station.
Coupling loss with opt-device	superior	inferior	It is important to reduce a cost of terminal equipment, because a number of terminal equipment are relatively more than other general systems . Using a fiber which superior to match with opt-device, become to get a cost effective terminal equipment.
Construction easiness of connector	superior	inferior	In case of using graded-index fiber requires highly accuracy to assemble a connector because effective core diameter is smaller than step-index fiber.
Cost effectiveness	—	—	It is difficult to compare a cost of both type of fibers because it depends on the production prosess. However, step-index fiber made of pure crystal in core part is more cheaper for no consumption of dopant.


Optical fiber cord
(with numbering)
Tention menber
(steel-strand wire)
(covered with
polyvinyl chloride)
Sheath
(polyvinyl chloride)

Optical Fiber Cable for Jumper


Optical fiber cord
(with numbering)
Tention menber
(steel wire)
(covered with
polyvinyl chloride)
Sheath
(polyvinyl chloride)
Upper winding Tape

Optical Fiber Cable for Equipment

Fig. 1 Construction of Optical Fiber Cable

video signal transmission, one for audio signal transmission, and remained two for spare uses. Cables have applied steel wires as tension members, and especially jumper cable have used steel stranded wires, thus flexibility being taken into consideration. The construction of the optical fiber cable with 6-core is shown in Fig. 1.

2.4 Construction of a Optical Connector Connection:

It follows that railway vehicles require jumper connector for connection of the optical fiber transmission route between cars.
In the jumper connector, engagement and disengagement used to be treated far more frequently compared with genetal optical fiber transmission circuits.
It accordingly is necessary to have such construction that losses caused by dust involvement resulting from engagement and disengagement may be minimized and not to arise axial misalignment in the optical axle.
Basic experiments have been made in three kinds of method in accordance with the requirement of the loss at the connector being 1.5 dB and less, and comparison was made.

(1)Fiber Matching Method:

The fiber matching method is the method of direct matching of polished fiber end surfaces. (Fig.2)
this method revealed that basic loss of about 0.3 dB will produce under most suitable connectiog condition, that the end surface intervals must be set at 0.2 mm and less to suppress the connection loss to 1.5 dB and less, and that the axial lateral misalignment must be kept less than +20μm to +30 μm.

(2) Autocollimation Method by Spherical Lenses:

The Autocollimation method by spherical lenses is such that spherical lenses are connected to the fiber end to produce parallel beam between opposing spherical lenses and to make them converge again at the fiber end which will be connected them. (Fig. 3)
This method revealed however that the basic loss is found at 2 dB even at the most suitable connecting and fails to satisfy the specifications.

(3) Autocollimation Method by Selfoc Lenses:

The autocollimation method by selfoc lenses is to produce parallel beam between opposing lenses and to converge again by fiber connecting end. (Selfoc lens is a cylindrical shape lens which is similar to magnifying core part of graded-index fibers.) (Fig.5)
This method revealed that the basic loss will be about 1 dB and that the axial lateral misalignment can be allowed to be about 0.1 mm and less in case the lens end surface intervals are 5mm and less even the connection loss is supposed to be 1.5 dB and less.
From the above-mentioned basic experiment under the selfoc lenses method, it reveals withstanding against dust adhesion for its wide connecting section, and easy prevention of influence of axial misalignment; thus development has been made with this method held suitable.

2.5 Countermeasure Against Transmission Route Troubles:

The transmission system where series transmission is being made by the loop topologies

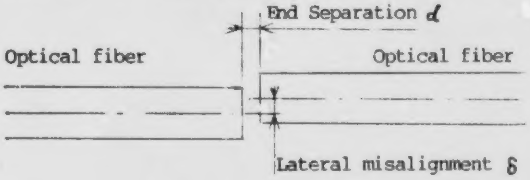

End Separation d
Optical fiber
Optical fiber
Lateral misalignment δ

Fig. 2 Optical fiber direct matching method

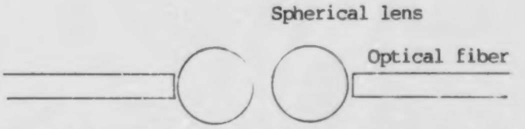

Spherical lens
Optical fiber

Fig. 3 Autocollimation method by spherical lenses

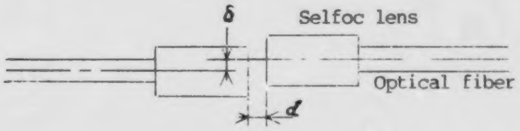

δ
Selfoc lens
Optical fiber
d

Fig. 4 Autocollimation method by selfoc lenses

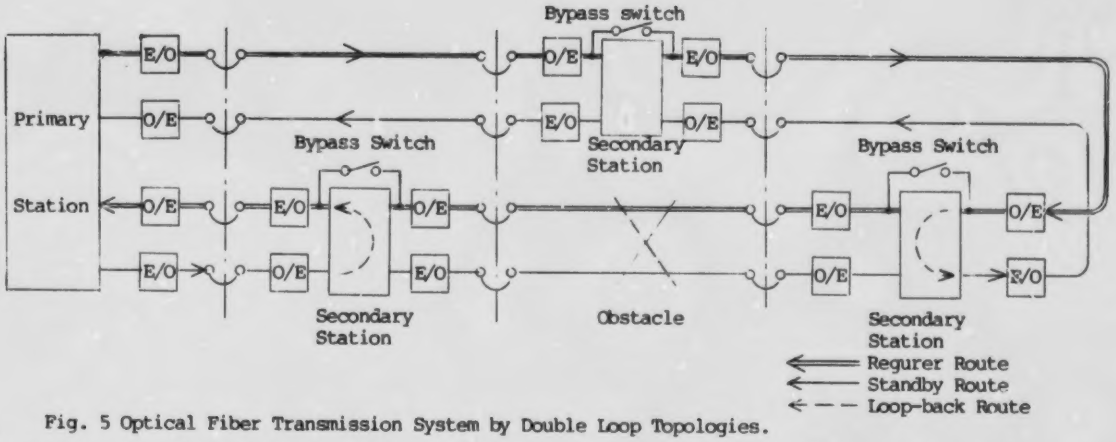

Bypass switch
E/O
O/E
E/O
Primary
O/E
E/O
O/E
Secondary
Station
Bypass Switch
Bypass Switch
Station
O/E
E/O
O/E
E/O
O/E
E/O
O/E
O/E
E/O
E/O
Secondary
Station
Obstacle
Secondary
Station
Regurer Route
Standby Route
Loop-back Route

Fig. 5 Optical Fiber Transmission System by Double Loop Topologies.

may lose the function of all the systems if such troubles as disconnection in the optical fiber and the like should occur in the transmission route. Against such occasion, it is necessary to take such measures not to cause losing fanction of the total systems in the transmission route.

For the purpose, a light transmission route including opt-electric converters is constructed by double loops. This is intended for maintaining the transmission performance by means of switch-over to the standby route or the loop back route in case of troubles. This situation is shown in Fig.5

3. Application of Optical Fiber Transmission System

3.1 Information Transmission Between On-board Controllers of Magnetic Levitation Vehicle:

The information transmission between on-board controllers of the Magnetic Levitation vehicle is made by optical fiber.

In terms of the characteistics, the Magnetic Levitation vehicle have strongly been requested especially of the light weitht in the apparatas to be mounted.

The optical fiber transmission ensures further light weight than those by means of axial cables, not to speak of comparison with conventional straight pull electric wires.

In addition, from the viewpoint that it will not hardly effected to strong magnetic fields caused by super-conductive magnet having been mounted on vehicles, the optical fiber demonstrates great advantages.

The system construction of this transmission system is shown in Fig 6.

The requirements of the transmission system are shown in Table 2.

The transmission route provides bilaterality by a optical distributor and is so designed to keep the transmission performance against troubles in a part of the transmission route.

This system was mounted on vehicles in 1982 and has been in satisfactory operation since.

3.2 Information Transmission Unit Between Chopper Controller of Light Cars of Hiroshima City Car:

The information transmission unit between the chopper controllers of light cars of Hiroshima City Car is taking information exchange with transmission made to obtain syncronous operation between chopper controllers. The system construction drawing of the transmission system is shown in Fig .7

The requirements of the transmission system are shown in Table 3.

TABLE 2
Specification of Transmission System of Magnetic Levitation Vehicle

Transmission method	Time-division multiplexing
Modulation	PCM-IM
Transmission rate	9.6 Kbps
Optical Transmitter	LED wave length 0.87 μm
(Optical power)	(-12 dBm min.)
Optical receiver	PIN-Photo Diode
(receive sensitivity)	(-45 dBm max. BER:10^{-9})
Optical fiber	Step-index core dia. 100μm NA:0.17
Optical cable	4 fibers blanketed
Optical connector	Water proof 4-poles connecting loss about0.5dB

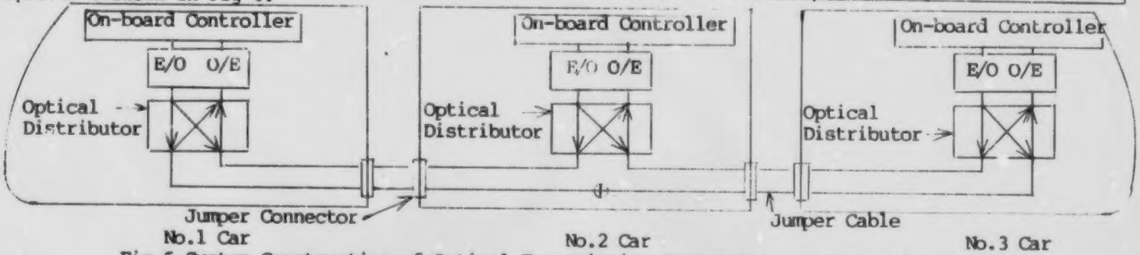

On-board Controller
E/O O/E
Optical
Distributor
On-board Controller
E/O O/E
Optical
Distributor
On-board Controller
E/O O/E
Optical
Distributor
Jumper Connector
Jumper Cable
No.1 Car
No.2 Car
No.3 Car

Fig.6 System Construction of Optical Transmission System Between On-board Controller

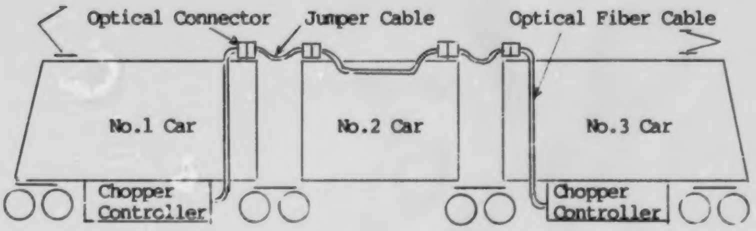

Optical Connector
Jumper Cable
Optical Fiber Cable
No.1 Car
No.2 Car
No.3 Car
Chopper Controller
Chopper Controller

Fig.7 System Construction of Optical Transmission System of Light Car

TABLE 3
Specification of Transmission System of Light Car.

Transmission method	Time-division multiplexing
Modulation	PCM-IM
Transmission rate	2 Mbps
Optical transmitter	LED wave lengh 0.875μm
(Optical power)	(-12 dBm min.)
Optical receiver	PIN-Photo Diode
(Receive sensitivity)	(-44 dBm max. BER:10^{-9})
Optical fiber	Step-index core dia. 100 μm NA:0.19
Optical cable	2fibers blanketed
Optical connector	Water proof 4 poles connecting loss about 0.5dB

This transmission system provides comparatively a high-speed transmission called 2 Mbps in terms of the synchronous timing. The optical fiber cable is conducting bilateral communication by two cores. Signals having seven channels are transmitted by a time division multiplexing.
With it mounted on board trains in 1980, the transmession contents of data have been checked for monitor errors since, revealing no troubles and showing satisfactory transmission characteristics.

3.3 Information Transmission System of Vehicles for Use of Trains Having Numbers of Cars

The information transmission system of vehicles for use of trains having numbers of cars has been developed for stabilized information transmission in electric cars of 10 to 16 cars. This system is constructed in considesation not only of the control information of vehicles but also of the transmission of video and audio signals.
The over all system construction is shown on Fig. 8, The requirements of the system are shown in Table 4.
As shown Fig. 8, the light transmission route provides each transmission unit in a staggered arrangement in each vehicle. Since the light signal can be amplified in each transmission unit, the connections between the transmission unit can be minimized at four spots and available for any affairs even the train has numbers of cars. The control information transmission system among them applies double loop system, being available for maintaining the transmission performance even in case of troubles in the transmission route.
The audio information transmission system provides overall broadcast in the vehicles and mutual communication by interphone between conductors room and passengers. The transmission of audio information depends on the exclusive use of one line of the 6-core optical fiber lines. The video information transmission system is available for transmitting guidance information to the monitor TV of each passenger room and for throwing the pictures that the TV camera caught the state in passenger rooms to the monitor TV in the operators room. Provided that the video signal may double the video sub signal by the FM modulation of the subcarrier. This system was mounted on the chopper control electric car of Yurakucho Line of Teito Rapid Trandit Authority in Sep., 1983, showing satisfactory transmission characteristics in this test.

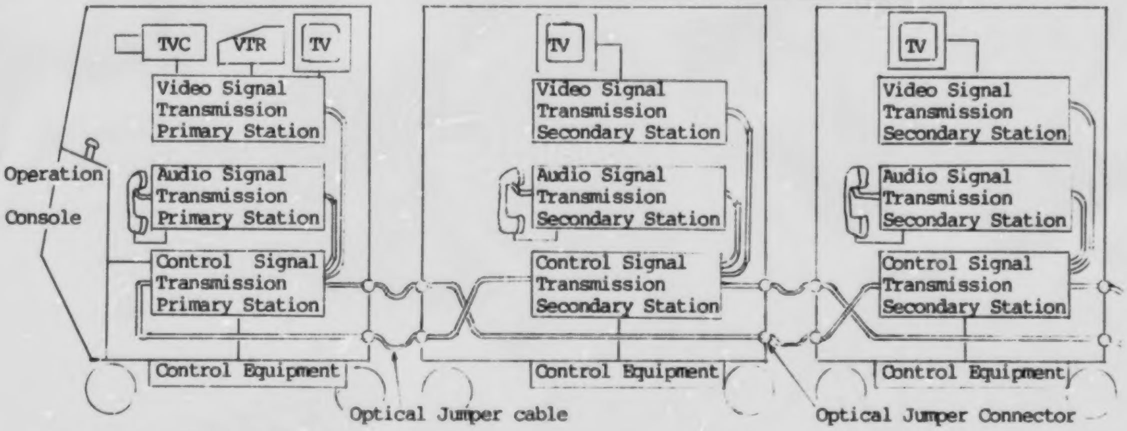

TVC
VTR
TV
Video Signal Transmission Primary Station
Operation Console
Audio Signal Transmission Primary Station
Control Signal Transmission Primary Station
Control Equipment
TV
Video Signal Transmission Secondary Station
Audio Signal Transmission Secondary Station
Control Signal Transmission Secondary Station
Control Equipment
TV
Video Signal Transmission Secondary Station
Audio Signal Transmission Secondary Station
Control Signal Transmission Secondary Station
Control Equipment
Optical Jumper cable
Optical Jumper Connector

Fig.8 System Construction of Optical Fiber Transmission System for Trains Having Number of Cars.

TABLE 4
Specification of Transmission System of Long Train Cars

	Control Signal Transmission	Audio Signal Transmission	Video Signal Transmission
Network	Douole loop (standby route,bypass,loop-back exchangeable)	Uni-directional loop	Uni-directional loop
Transmission method	Go-Ahead polling ,SDLC	Circuit exchange	Broadcasting
Modulation	PCM-IM	Double integrated ΔM-IM	Base band direct IM (video signal) FM-direct IM (sub signal)
Transmission rate,band	48 Kbps	32 Kbps (Audio band 200Hz 3KHz)	50Hz 6MHz 200Hz 6KHz (sub signal)
Optical transmitter (Optical power)	LED wave length 0.85 μm (-11 dBm min.)		
Optical receiver (Receive sensitivity)	PIN-Photo Diode (-37 dBm max. BER:10^{-9})		
Optical fiber	Step-index Core dia. 100 μm NA: 0.17 loss 5 dB/km		
Optical cable	6 fibers blanketed Outside diameter 13mm		
Optical connector	Water proof 6 fibers blanketed		

3.4 Vehicle Control Information Transmission Unit for Use of Experimental Electric Car of Ginza-marunouchi Line of Teito Rapid Transit Authority

The vehicle control information transmission unit for use of Experimental Electric Car of Ginza-Marunouchei Line of Teito Rapid Transit Authority is the optical fiber transmission unit performing a function of transmitting the control information of vehicles. In other words, this is designed for transmitting the control information having conventionally been transmitted by a large number of passing wires by means of the transmitting system by optical fiber .
The system construction is shown in Fig. 9.
The requirements of the transmission system are shown in Table 5.
the construction of the optical fiber transmission system is nearly the same as the part of control information transmission of the above mentioned Item No.4-3
In addition ,an operation panel and a plasma display for monitoring the transmission condition are attached.
This system has taken long-term test since it mounted on an electric car in Sep. 1983. It showed excellently a satisfactory transmitting characterestrics up to the present.

TABLE 5
Specification of Transmission System of Subway Cars.

Network	Double loop (standby route,bypass,loop-back,exchangeable)
Transmission method	Go Ahead polling ,SDLC
Modulation	PCM-IM
Transmission rate	64 Kbps
Optical transmitter (Optical power)	LED wavelength 0.85 μm (-11 dBm min.)
Optical receiver (Receive sensitivity)	PIN-Photo Diode (-37 dBm max. BER:10^{-9})
Optical fiber	Step-Index Core dia. 100 μm NA:0.17 loss 5dB/km
Optical cable	6 fiber cords blanketed Outside diameter 13mm
Optical connector	Water proof 6 poles

4. Conclusion:

As started so far, it was revealed that the optical transmisson system has high reliability and very low error rate in spite of such considerably a bad circumferential conditions as in railway vehicles.
The optical fiber transmission system is very suitable as an information transmission system of vehicles and will take the lead of the information transmission system in the future.

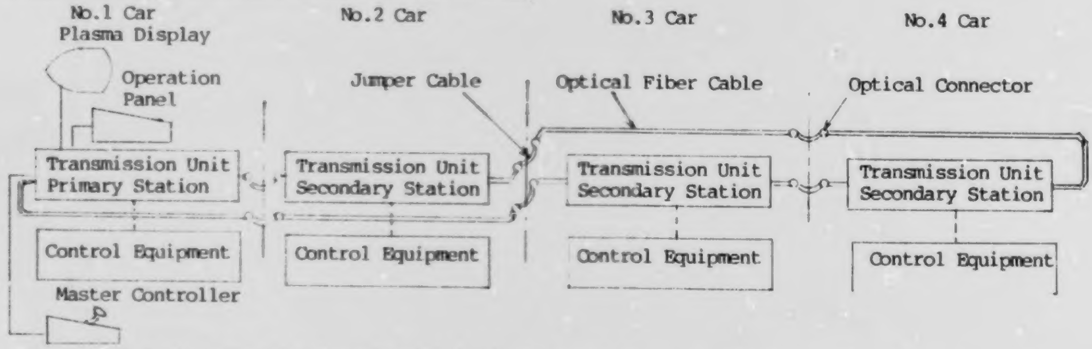

No.1 Car
Plasma Display
Operation Panel
No.2 Car
Jumper Cable
No.3 Car
Optical Fiber Cable
No.4 Car
Optical Connector
Transmission Unit Primary Station
Transmission Unit Secondary Station
Transmission Unit Secondary Station
Transmission Unit Secondary Station
Control Equipment
Control Equipment
Control Equipment
Control Equipment
Master Controller

Fig.9 System Construction of Optical Fiber Transmission in Subway Experimental Car

TECHNOLOGY ADVANCES IN SIGNALLING SYSTEMS UTILIZING VITAL DATA COMMUNICATION

W. Friesen
Manager of Engineering
ITT SEL Canada

Summary

Application of vital data communication links, taking full advantage of modern computer technology to safely and economically provide all control functions required in modern railroad applications, is discussed. The requirements of effective railroad traffic flow, from unsignalled territories through to a fully controlled territory, can be met by utilization of vital data communications for simple modular implementation of an easily expandable system.

History

The integrity of communication links used for control of safety functions (commonly known as "VITAL" functions) has been an important subject since the early days of train operation.

Hand signals and flags were likely the earliest methods used for communication of "VITAL" information to prevent train accidents. By the 1830's this had evolved to the point of advanced announcement of a train's performance relative to schedule. Signals were located at each station and at intervals between stations. If a train departed on time the station attendant hoisted a white ball, or if late, a black ball. This was observed by telescope from the next signal location and a ball of the same colour was displayed. By repeating this procedure from signal to signal, a train's departure was known at the next station, miles ahead, in a relatively short period of time.

The integrity of this system required that the people at the intermediate locations observed correctly as well, raising the correct ball themselves.

This method of communication was soon replaced by the telegraph. Safety was then delegated to station operators who received information about trains via telegraph messages. Trains were to proceed into the next territory (commonly known as "BLOCK") only if it was known to be "CLEAR" (free of all other trains). Unfortunately, it was soon known that this method of information exchange provided inadequate protection against errors.

A better method of communicating, in a "FAIL SAFE" manner, that a block was occupied by a train, was needed.

Major progress came in the 1870's. The Direct Current track circuit provided automatic block occupancy detection. With hard-wired circuits, they then provided a far more secure communication of the train's position to the operators. No longer did he have to hope that correct information was sent by others.

Progress in the continued search for a Vital (very, very low probability of an undetected error) communication link has been largely in the area of hard-wired electro-mechanical circuits. Consequently, safety related control equipment is located at trackside (near switches, signals, etc.) and supervisory control equipment is often centralized, for larger territories. NON-VITAL communication links provide for remote control functions.

Conventional Systems

Most implementations over the last 30 to 40 years have had configurations as shown in Figure 1 below.

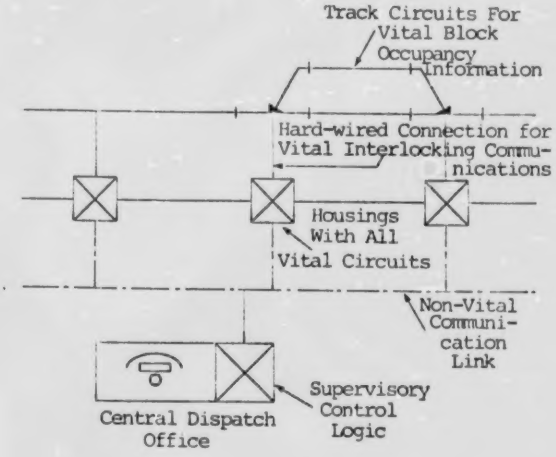

Track Circuits For Vital Block Occupancy Information
Hard-wired Connection for Vital Interlocking Communications
Housings With All Vital Circuits
Non-Vital Communication Link
Supervisory Control Logic
Central Dispatch Office

Figure 1 The Conventional Signal System

In these configurations all vital communication is located at trackside and requires hard-wired interconnection for the length of the railway. Communication of the information to the train driver is generally via wayside signals which must be "seen".

The NON-VITAL communication link, from the Central Dispatch office to the field sites, can be any form and often utilizes combinations of line carrier, microwave or radio. Any data errors represent only an annoyance as all safety functions are "hard-wired" in the wayside equipment.

The dynamic nature of present railway systems requires the control system to be adaptable and flexible. In addition, efficiency improvements including maximum track utilization, often bring a need for shorter headway operation. These demands cannot easily be met by control systems which are physically located in a distributed manner along the railway. The need for extensive hard-wired distributed logic is due to the needs of "Vital Communication".

The cost of new sidings, relocating rail switch points or adding signals is high. These costs are the result of the labour intensive nature of installation and safety verification. Additionally, there is a cost due to loss of the signalling system (and thus railway operations) during the reconstruction and commissioning phases. Rail systems are very sensitive to these delays, as throughput is lowered at a time when increased capacity is needed.

It is thus desirable to have systems, including vital communication links, which are easily reconfigured and minimize both the installation labour and train operational impacts.

Computer Control Developments

During the mid-60's and early 70's significant development, on the use of computers for vital applications, took place in Europe. This led to the installation, in 1972, of a computer control system "CORECT", for high speed (200 kph) trains, between Hamburg and Bremen, in West Germany. The development was undertaken by ITT and involved the use of three computers in a "two out of three" voting arrangement to provide for "VITAL" capabilities. Continued expansion of the system on the railway is an indication of its acceptability and success.

This system was configured as shown in Figure 2 below.

In the application mentioned, the objective was to operate 200 kph trains on track previously signalled for much lower speeds. Upgrading was done without changes to the existing signalling system.

In order to achieve this, a "vital communication" link needed to be established between the train and the wayside computer system. With this link in place it was possible to provide VITAL commands directly to the locomotive, in advance of the wayside signal. Furthermore, the trains could proceed past an approach signal at a higher speed, provided the on-board computer system identified that adequate braking distance was still available for the train.

Application of computer technology provided the capability to incorporate a large number of vital commands without the use of hard-wired circuits. In the 10 years since this demonstration, many advances have been made in the use of microcomputers for implementation of signalling logic, however, VITAL DATA COMMUNICATION has not been addressed as widely.

Vital Data Communication

Fundamental requirements, which need to be satisfied, for a VITAL DATA COMMUNICATION link requiring an exceedingly low rate of undetected failures, are not new. They apply equally to the man with the telescope, of 150 years ago, and to the computer systems, now being implemented. In both cases information must be accepted only if it can be assured that the information is correct. Erroneous or corrupted

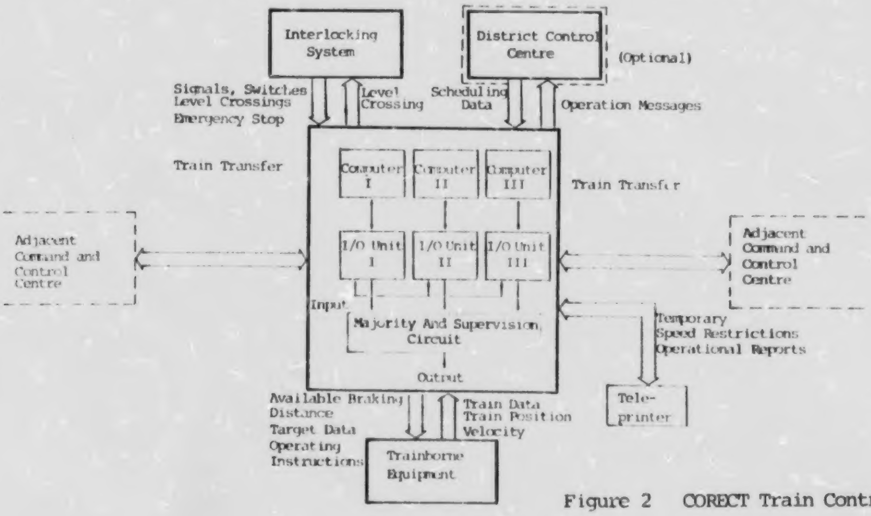

Interlocking System
District Control Centre
(Optional)
Signals, Switches
Level Crossings
Emergency Stop
Level Crossing
Scheduling Data
Operation Messages
Train Transfer
Computer I
Computer II
Computer III
Train Transfer
Adjacent Command and Control Centre
I/O Unit I
I/O Unit II
I/O Unit III
Adjacent Command and Control Centre
Input
Majority And Supervision Circuit
Temporary
Speed Restrictions
Operational Reports
Output
Available Braking Distance
Target Data
Operating Instructions
Train Data
Train Position
Velocity
Tele-printer
Trainborne Equipment

Figure 2 CORECT Train Control System

information must be identified and responded to in a "SAFE" manner. Most frequently, the "SAFE" action is to avoid using the information and indicating that an error has occurred. If the errors continue, more radical action needs to be taken to ensure that no future unsafe result will be accepted.

A primary requirement of any vital communication link is that the subsystems at both the transmission and reception end of the link must be vital. This may sound very basic, but it is often not considered. If one cannot expect that the systems sending and receiving the data are in themselves vital and able to ensure that they behave predictably under all failure conditions, then it is not possible to extract the conveyed information in a vital manner. Thus, in order to achieve vital communications, the equipment AT BOTH ENDS MUST BE VITAL.

Further, integrity checking must be implemented to ensure that even under the worst error rates, it is always possible for the terminal equipment to identify bad information. Some techniques used to ensure this are:

- Redundancy checks performed on data transmitted to enable rejection of data corrupted through interference.
- Transmitted data is updated cyclically. Commands transmitted are updated or confirmed in each new cyclic message. (Cycle times need to be frequent enough to enable bounding of erroneous data.)
- Credibility and persistency checks need to be performed on received data. The terminal equipment, at both ends, checks data with respect to a "reasonable" value based on previously accepted information.

These fundamental principles have been applied, in one way or another, whenever vital information needed to be exchanged. It is different in application however, when the terminal equipment has the capability for programmed logic. This capability, when implemented as vital terminal equipment, now allows any communication medium (radio, carrier land line, microwave, etc.) to become useful in transporting VITAL DATA.

Flexibility and capability of Train Control Systems can now be expanded substantially.

Application Of Vital Communications

In the development of the earlier (1970-75) applications, such as the ITT "CORECT" system on the German Federal Railways, it was convenient to use the existing wayside equipment to control rail switch points. However, to achieve an effective "overlay" system it was still necessary to implement a VITAL COMMUNICATION LINK for the reporting of switch and signal statuses to the "CORECT" computer system.

The tools were now in place for a new generation of train control systems. Developments, such as magnetically levitated systems and linear induction motors, dictated that track circuits could not be implemented for train location (or "BLOCK OCCUPANCY") purposes.

An adaption of the CORECT system, known as "SELTRAC", was implemented for train control utilizing an inductive loop as a communication medium between a vital wayside computer system and a vital computer system on-board the train. Additionally, a vital communication link, utilizing land line carrier, was implemented to allow the vital wayside computer system to control the movement of rail switch points. All interlocking functions are implemented in the vital wayside computer system.

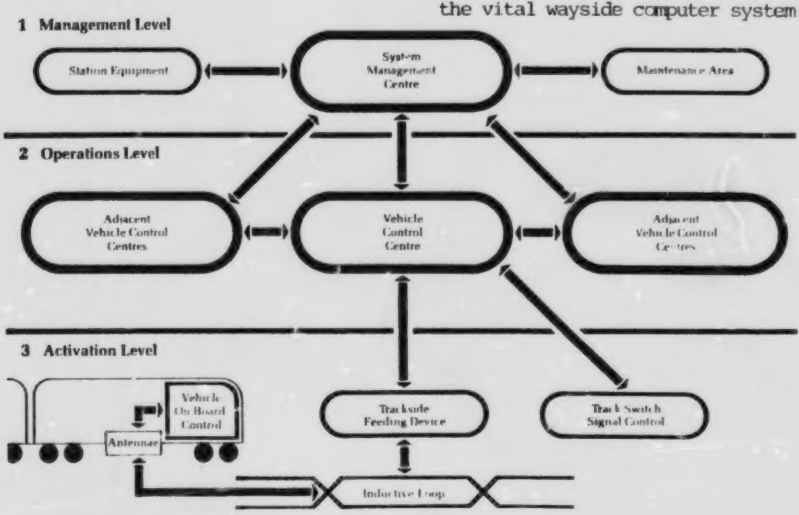


Figure 3 SELTRAC Train Control System

Figure 3 shows the equipment configuration for a typical SELTRAC system.

Concepts

Provision of safety in the operation of trains can be identified as:

- ° Enforced train separation (VITAL)
- ° Switch locking with respect to train location (VITAL)
- ° Train speed limit enforcement (VITAL)

These functions are implemented effectively with the use of vital microcomputer systems on the train, at a wayside control location and at the rail switch point location. This network of vital "terminal points" can now be interconnected with conventional communication links, and techniques for vital data exchange, to form a VITAL NETWORK for supervision of trains.

The Moving Block

Figure 4 shows how this supervision is implemented by providing to the Vital On-Board Control (VOBC) system, information on the maximum allowable train speed and stopping point. The communication is updated cyclically to ensure that continuous updates are available to the train. The VOBC continuously calculates the stopping distance required for the train at its prevailing speed. Because of the high resolution of the on-board position detecting system, a following train may safely close up to a point of safe braking distance from the last verified position of the rear car of a preceding train. In many applications a significant reduction in headway relative to fixed block systems, is possible.

Because of this feature, no Train Control System changes are necessary when closer headway follow-on movements of trains are required. If overlaid on an existing conventional signal system, the signal aspects are reflected in the supervised speed and allowed position profile.

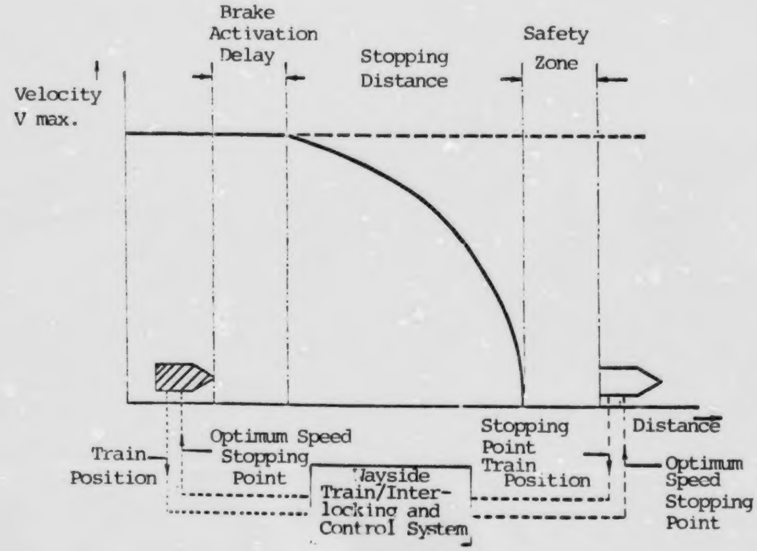
The "Safety Zone" is a distance such that should a train go into maximum acceleration, when it is already in the braking curve, an emergency stop is still ensured (by the VOBC) before the next train is reached.

The wayside Train/Interlocking and Control System (TICS) is a vital computer system which constantly scans the track for other trains or switches and advances the stopping point only when everything is CLEAR. In this way, the train will always have a "safe" stopping point, even if there is an interruption in the vital communication system.

Switch Control

To provide for the vital control functions required by the switches, another microprocessor system (VITAL) is implemented. Equipment type and configuration is similar to the Vital On-Board Control. This microprocessor system is refered to as SELSIG.

The SELSIG subsystem provides for a vital communications link between the control computers (TICS) and wayside equipment such as switch machines, block occupancy detection (overlay systems) and other such data. For system flexibility the VITAL DATA COMMUNICATIONS link can also be established between SELSIG units located along the track.



Brake Activation Delay
Stopping Distance
Safety Zone
Velocity V max.
Distance
Train Position
Optimum Speed Stopping Point
Wayside Train/Interlocking and Control System
Stopping Point Train Position
Optimum Speed Stopping Point

Figure 4 The Moving Block

A Flexible Control System

Extensive utilization of vital communication links allows a new more flexible train control system to be implemented.

Shown in Figure 5 is an overall schematic of an implementation made possible using the described techniques.

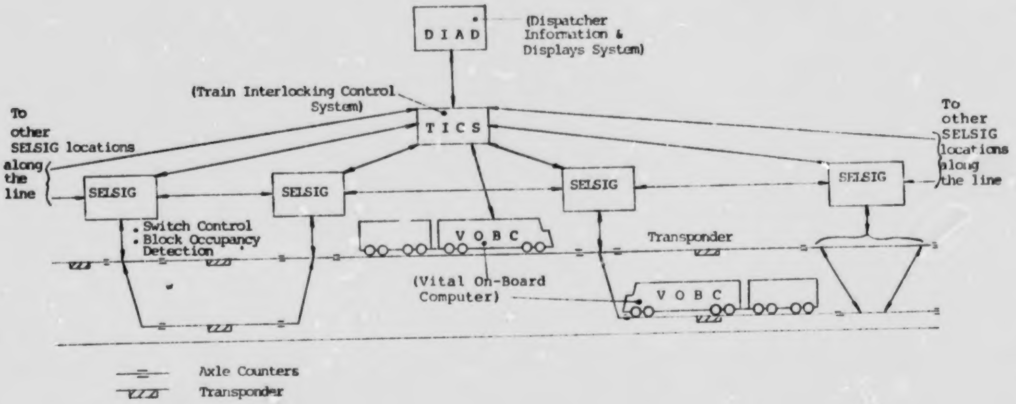

D I A D
(Dispatcher Information & Displays System)
(Train Interlocking Control System)
T I C S
To other SELSIG locations along the line
To other SELSIG locations along the line
SELSIG
SELSIG
SELSIG
SELSIG
• Switch Control
• Block Occupancy Detection
V O B C
V O B C
(Vital On-Board Computer)
Transponder
Axle Counters
Transponder

Figure 5 SELTRAIN Train Control System

This Train Control System, known as "SELTRAIN", has four basic control levels:

- The Central Dispatcher Information and Display (DIAD)
- The Train/Interlocking Control System (TICS)
- The Vital On-Board Control (VOBC)
- The Vital Wayside Control Logic (SELSIG)

All of these system elements, except the DIAD, are implemented as vital systems.

Two additional elements not previously mentioned are also integrated into this system. They are:

- Axle Counters
- Transponders.

Axle Counters

As shown in Figure 5, wayside block occupancy detection is achieved by an axle counter system which eliminates rail bonding and insulated joints. Furthermore, any length of block can be achieved (track circuits are limited to about 1.5 to 3 km), simply by locating the detection heads at the appropriate positions.

By counting the number of axles moving in and out of the track section, and declaring it "clear" only at a count of zero, it is ensured that no cars will remain on this particular track section. Redundancy and special information handling techniques ensure that the function is executed in a vital manner.

It should also be noted that the flexibility of the described train control system allows the use of track circuits to provide information on track occupancy.

The wayside block occupancy detection system allows operation of trains not equipped with a VITAL On-Board Control unit.

Transponders

Passive transponders need no local power source; they are mounted on the ties and provide exact wayside position data to the VOBC. The information transmitted includes:

- exact train position on the track
- civil speed limit at this point
- distance to the next transponder.

In the event of a data communications interruption with TICS, the train continues operation on the basis of such information.

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Train Operation

In contrast to conventional systems, the Train Control System shown in Figure 5 differs in that wayside equipment is reduced to the minimum required for the operation of switches and for block protection.

Operational capabilities include:

- Cab Signalling Operation for trains so equipped, and train order operation for non-equipped trains.
- Vital reporting of train position and its speed.
- Vital block occupancy detection and information for all trains in the territory.
- Vital speed and position supervision for equipped trains.
- All expected activities are automatically and continuously compared against train performance, e.g. train position vs. train order.
- Vital train separation protection.
- Vital switch control and switch position supervision.

Usually, the dispatcher is provided with a colour graphics monitor which shows the track in the respective territory and the position of each train on the track. Hence real-time information on the activities of each train is obtained. The monitor also indicates each controlled switch position and alerts the dispatcher to a locked (or unlocked) switch status.

The dispatcher also has available a black and white CRT so as to prepare train orders and command train routing information. On request, a representation of a train order and routing appears on the screen.

The SELTRAIN equipped trains entering the territory automatically identify themselves to the computerized system. The system, in turn, notifies the dispatcher of a new train arrival by flashing a message on the CRT. The dispatcher can now clear a route for the train.

Motion of trains is controlled by TICS which, according to the train route priority and track occupancy, assigns a target point, a switch position and a speed profile to the train. The distance to the target point and the allotted speed profile are presented on the on-board display.

For trains not so equipped and which are entering the territory, the dispatcher must revert to train order operations, but the task of monitoring the position of trains is greatly simplified. The engineman notifies the dispatcher via voice communication that the train has entered the territory. This is also confirmed by the indicated block occupancy in TICS.

Train orders are entered into the system via a keyboard. The system maintains a temporary filing system for all train routes which were prepared by the dispatcher. These can be printed on hard copy if required.

The dispatcher then assigns a train number to the train entering the territory. From this point on the dispatcher tracks non-equipped train movements in the territory by monitoring information on block occupancy and switch position.

Should the TICS determine that a violation exists between two trains, the equipped trains involved are emergency braked and an alarm sounds to alert the dispatcher. He then intervenes to facilitate stopping of non-equipped trains.

The system also monitors all information with regard to train orders, train position, etc. and alerts the dispatcher in case of any discrepancy, e.g. if a train's position does not agree with the train order.

If an unequipped train inadvertently enters a track section which is already "occupied" by an equipped train, the system alerts the dispatcher and automatically stops the equipped train.

Through a direct input to TICS the dispatcher has the ability to enforce speed restrictions at any time or for that matter to "close" a track. Equipped trains will not be able to violate this dispatcher's instructions.

System Benefits

The benefits of a train control system as described here are achieved by the modular design, flexibility, ease of adaption to requirements and reduction in wayside equipment and its associated maintenance.

The Train Control System enhances present signal system concepts by incorporating an additional vital control link between the locomotive and the Train/Interlocking Control System. Since the traffic system performance is based on three parameters (train, track, dispatcher), this additional link allows supervision and system performance optimization not possible heretofore. This is especially true because it provides continuous monitoring and optimization at all three levels of the traffic control system.

Various levels of automation/dispatcher aids can be provided as required, including a Train Operation Management System which provides conflict detection and resolution by automated forecasting and advance planning. Furthermore, the ability to stop a train by direct command enchances safe train operation.

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Increased territory capacity is possible due to the ability to provide following train movements with reduced headways between equipped trains.

The ability to slow or stop trains as desired results in reduced wear of materials and reduced fuel consumption. Trains will continue to operate at the same average speed, but this is accomplished by more continuous movements and less operation at higher speeds with subsequent stops.

Train speeds and safe stopping points are enforced by the train control system to enhance operational safety. Supervision of these critical parameters is obtained by the on-board locomotive equipment which continuously monitors present performance against allowable safe values determined by the vital Train/Interlocking and Control System.

System flexibility allows the implementation of add-on equipment to full system capability. In this way, a railroad could first install a greatly simplified system (NON-VITAL) for dispatcher information. This economical feature would eliminate the checked-redundant computer systems since it is only an information system. As traffic requirements increase more subsystems can be added leading to full VITAL capability of the SELTRAIN system.

Q & A SESSION
ADVANCED SIGNALLING AND CONTROL

QUESTION (MR. GHALY, NYCTA): It's a question for Mr. Pascoe (US&S). I'd like to know what's the function of the wraparound discrete hardware in the microprocessor?

ANSWER (MR. PASCOE): The wraparound hardware, as a number of systems showed, we have the processor with dual path programming, and then to talk to the outside world, what we consider wraparound hardware would be the monitors, the toggle and also the conditional power supply. The wraparound then ties the processor to the heart of the system and it talks to these peripheral devices. And the three pieces we have in concept anyway is the conditional power supply which supplies instant energy if all the diagnostics prove good. It supplies energy so we can talk to the outside world. And then we always check the input and output monitors in concept when the processor has to interface to the outside world. That's what we mean by discrete wraparound hardware.

QUESTION: But basically, the safety of the system, does it depend on this wraparound?

ANSWER: The conditional power supply is traditionally a vital piece of hardware in discrete electronics. The monitors may be, because there are some current level measurements that have to be done vitally, but the concept of toggling is, as many others discussed here, that you know the state you're going to, you check if you've gone to that state, and there's a constant look back type checking done. But there is some discrete vital hardware associated with our concepts.

MR. HOELSCHER (MODERATOR): Any other questions?

QUESTION (FRANK SWITHERS, DeLeuw Cather): In GRS presentation, he pointed out that they drive a vital relay as a check circuit. Does that mean your system is no more reliable than a vital relay? Is it subject to the same unsafe failures that vital relay is subject to?

ANSWER (MR. SIBLEY): I thought the unsafe failures of vital relays were pretty low and we weren't too concerned with them. If this is a problem, you can always put two vital relays in series.

QUESTION: If vitality of the system you have is no better, why not leave it the way it is? Well, that doesn't answer my first question. Is it true that the system is no more reliable than a vital relay?

ANSWER: I think you can say that is true, and we have accepted the vital relay for an awful long time as being something that we have absolute faith in. Now as I mentioned, if you have any reason that you want to go to redundancy or series connections of more than one in order to feel better about the vital relay, there's no reason why you can't do that.

QUESTION: [inaudible]

ANSWER: I think our goal is to make these new systems as safe and as reliable as the old systems. We don't want to lose anything as we take advantage of the new technology. And the reason for going to the new technology was that we were capable of doing more things. As some people have pointed out, we can probably do them for less money, and we can do them with great space savings. So the new approaches are very attractive.

QUESTION: I'm Neal Brumberger, and I'm from the Bay Area Rapid Transit District (BART). I have a question that is actually directed at all the panel members, and I don't particularly care in what order it's answered. But I would like to know what the internal safety criteria is that has been set by each of your companies for developing or utilizing LSI electronics in vital applications. And specifically, the question is do you use a quantified mean time between hazard or mean time between unsafe failure, and if you do, what is the number? And why don't we just start on one end of the table and work on down. I know Westinghouse's number. I gave it to them, but I'm curious what you other guys are doing.

ANSWER (MR. FURNISS): We on British Rail, we're like this. You've got to make a lot of assumptions. I've got a list here, so excuse me just a moment. There were no design errors in the system, and that's being optimistic (laughter). That all failures result in an unsafe condition. Now that's very pessimistic actually, because in actual fact, many failures don't cause unsafe conditions. That any subsequent failure renders the first and itself undetectable. This is very pessimistic. In actuality, that happens very rarely indeed. The mean time between failures per channel of the system is greater than 10,000 hours, and that's very pessimistic as well. The default detection coverage is such that the mean time to detection of the failure is one second. And that for our system is very realistic. Then the optimistic assumption and pessimistic assumptions cancel each other out. In other words, that one you laughed at in the beginning is canceled out by the ones I've just said later than that. Right, the vital figure that you're after, the probability of failure is two times ten to the minus four (i.e., 2 x 10^{-4}) per hour. The probability of subsequent failures before detection of the first is ten to the minus four divided by 3600, which is equal to two point seven times ten to the minus eight (2.7 x 10^{-8}). The probability of a dangerous failure is four point seven times ten to the minus eight (4.7 x 10^{-8}) per annum, if that means anything. You've got to take into account all those assumptions.

QUESTION (NEAL BRUMBERGER, BART): So that's something on the order of ten million hours, one unsafe failure in about ten million hours -- something like that.

ANSWER (MR. RICHARDSON): As Neal had mentioned for the BART ATC program the number that we have for design criteria is the mean time between unsafe failure of 250,000 years that we have to show. This is going to be a challenge, particularly with the micro-processor system and the real key is the amount of checks you do and how quickly you do them. We're trying to get at the minimum a lot of checks being done every eighteenth of a second in which time you should be able to say whether a failure has occurred. In the check redundancy you're trying to make sure that what is the likelihood of both channels failing in a compensating way during that eighteenth of a second. During the time that you can do a check.

ANSWER (MR. FRIESEN): I think by now the methodology used at deriving how hazardous a system is, is becoming fairly clear. What one wants to do is insure that any failure that's identified or identifiable or perceived is treated as a hazard during the hazards analysis. So if you have a basic failure rate for an IC or an LSI whatever it might be, that failure rate then is immediately plugged into the hazard analysis as though that failure in itself would automatically create a hazard. It is a very conservative approach, because many, many failures don't naturally create hazards. They fail in such a way that no hazard is generated. On the other hand one cannot play with how the failure might happen because the signal analysis and the detail check analysis would become unwieldy and virtually impossible to deal with.

Now furthermore, the hazard rate -- and yes, we do, Neal, we do use a hazard rate. We don't use some systems saying, yes, it is failsafe or it's vital. We calculate a hazard rate, but we do it on the basis of a single level of hazard. In other words, we don't say something is almost vital. The impact of this particular failure would be something undesirable, but nobody would die. We don't go into that layer of analysis. We simply say, if there is a hazard, it must have a probability of occurrence for the entire system of less than ten to the minus nine per vehicle operating hour.

ANSWER (MR. HARTKOPF): The reliability of the whole system of the interlocking is the same as relay interlocking. The MTBF of the Siemens SIMIS micro-computer is ten thousand to fifty thousand hours. For security (safety) failures, time between . . . .

ANSWER (JIM HOELSCHER): Ten to the power of fourteen (i.e., 10^{14}) hours is what he's saying for time between multiple failures.

ANSWER (MR. HARTKOPF): Security failures.

ANSWER: Security failures. Ten to the fourteenth hours.

ANSWER (MR. SIBLEY): We try to follow the traditional approach wherever we can with this sort of thing of designing for zero unsafe failures. We identify all of the hazards. We have a very strict safety analysis. We have a designer document his work fully, the checkers -- the design reviewer checking this. Our concept is essentially one in which we can design the processor to do a certain task and we can check to see whether certain hazards exist or not and do something about them. It's what you might call a closed loop concept. Where we can come up with a figure as the other gentlemen have pointed out, we are stuck with the fact that we don't know how many failures can be the bad kind, and we take the very conservative approach which simply gives us an upper bound on how bad things can be, probably off by a factor of several million, because usually if something fails in the processor, you don't get anything out of it. But anyway we have heard the words bandied about and that experience with the vital relay has been something like one unsafe failure in a hundred years, and we can make the figures indicate that can reach that order of magnitude in our analysis.

QUESTION (MR. BRUMBERGER): So you're saying that, say, for one typical vital interlocking your mean time between hazard would be what? Once per hundred years per interlocking or once per hundred years for the equivalent number of relays for that interlocking?

ANSWER: For that interlocking.

QUESTION: Once every hundred years, right?

ANSWER: We're trying to approach the security of the relay systems. I think traditionally as we've gone from one technology to another in the industry, we make sure that we haven't lost anything in safety, and we are still maintaining that tradition.

ANSWER (MR. PASCOE): We're in a similar situation. I think one unsafe failure in a hundred years equates to something like ten to the minus thirteenth for a single vital relay, and depending on the size of the system, etc., I would imagine we're talking about an unsafe failure, but not necessarily of creating an accident or death or whatever something like one in ten years. Probably the one in a hundred is fatalities or something equivalent to that. And in our systems we have a very rigid RAM program. The analysis is done, and our goal is the vital relay, the historical data collected by the vital relay. We have a similar problem on, as an example, safe braking distance. The same concept. When you throw a probability in, you wind up trying to pick and choose, and that's a difficult thing to be in. You're trying to have some bounds on it. And just specifically to say I have one given number, that's a very difficult concept to grab hold of.

ANSWER: Most of the questions and responses dealt with the hardware, that the hardware is not going to fail. How are you going to demonstrate that the software you put in it is safe?

QUESTION: Anybody or everybody? Everybody.

ANSWER (MR. FURNISS): We use a system on British Railway. We use a system of software validation which is a long and detailed analysis of our software. As you can see from my description, the software only has to be validated once for all different configurations. So we can afford to put an awful lot of effort into it. And we use functional analysis, struc-- all the titles of different things. I can go into more detail if you want to. There is functional analysis, structural analysis, modular validation, information flow analysis, semantic analysis, time analysis and system tests. The essential thing about it is that the program is a very simple, very simple structure. It's modular, and it's written in assembly code. This is necessary, we feel, for the type of use that we're putting it to, and we don't use things like interrupts, and everything is kept reasonably simple so that it can be easily validated.

ANSWER (MR. RICHARDSON): We also use many of the items that he mentioned. I have mentioned also we use assembly code so we can control better where things are placed. We do use interrupts for our system. In previous systems the customer had independent analysis of our safety. Batelle Institute looked at the San Paolo, and then we would respond to the comments that they had. For the BART system there's also an independent consultant and we are working with BART and their consultants to develop the safety verification plans.

ANSWER (MR. FRIESEN): Again for a start, I have a little bit of a problem with the concept of software failures. I do have a great deal of sympathy with software problems, however. Once software has been written, certified and proven valid and correct, then failures of sofware represent in fact hardware failures which generate incorrect responses on the part of the computer. Now what we do is go through something very similar to what British Rail does, a very extensive and very thorough software analysis as it's being written. Again, the interlocking logic portion of the software is a standard logic which was developed earlier, as early as the 1972 installation. That interlocking portion of the software, in fact, stays the same from project to project because only the site-specific, data-related elements end up being changed. What one has to do is to stay very, very close to the software and certify it quite independently, both on paper and in operation, from the people that write it. The certification process has to be a very detailed analysis of the software, a very detailed analysis of its reaction, which must include a full, real environmental simulation of the system prior to it ever being installed in the field. After it's installed in the field, it has to go through the same sort of operating check as any signaling system that you would install. Again, the process is one of validation and assurance, rather than saying that it will or will not fail.

QUESTION (MR. SWITHERS, DeLeuw Cather): Could I raise a point at this point? I have never been at a major interlocking cutover where circuits did not have to be changed because operation found something wrong. That's what I'm talking about, as software problems. You've validated something. You found when you went to operate it, it didn't work the way you thought. How do you handle that instance?

ANSWER (MR. FRIESEN): That's where it's so vitally important that the simulation exercise I was talking about is done prior to getting it in the field. The simulation exercise in the systems is one where the entire set of hardware is operated, and a simulator in fact acts as the trains on the track. You operate then in the design environment the railway as it would be operated in real life, and those types of problems are identified before you actually end up in the field. If, however, you have a change that has to be made once the system is in the field, and that's always a possibility, whether it be during initial installation or afterwards when a change gets made. Then that change has to go through that same verification process before it can end up in the operating computer in the field.

ANSWER (MR. HARTKOPF): Design errors in respect of software are avoided as much as possible by means of the following measures. At the present time the range of the program is limited in Germany to eight thousand commands. You can have more than one program in your micro-computer. The programs are clearly, logically and systematically arranged in program modules of 100 commands on average. The rules of structured programming are applied. The documentary chain is used to support clearness and completeness. Finally the programs are tested in several steps before the start of system testing and checked by two independent testers.

ANSWER (MR. SIBLEY): I think the various methods have been described. I think we're all trying to do the same as we've done traditionally with relay design: to design the system and then check it. The VPI has one program which remains the same for all interlockings. It changes from one piece of geography to another just in the data base, so once the program has been checked, then it's only necessary to check that the data base expresses what the signal designer wants it to do. And after, when the system's installed, they can be tested by the same breakdown test that we put on relay interlockings in the field. Changes, if they're necessary, will once again go back to the same rigorous analysis before we would accept any of the changes.

ANSWER (MR. PASCOE): Our user program, the compiler with the design -- signalman designing the circuit and using his traditional circuit as a flowchart. Anticipating these kinds of problems, the user compiler was developed so that he can use Boolean expressions and burn a PROM. In the field then if there are changes, as Frank points out, in any tradition[illegible] the operational checks, new PROMs [illegible] very easily burned and operational breakdowns or tests done for the changes. Keeping some of the traditional concepts or most of them in the preliminary design is very helpful to eliminate these software, quote, "problems," unquote.

MODERATOR (J. HOELSCHER): Okay, right now it's time for a coffee break. Reserve your remaining questions for the following panel session.

PANEL SESSION

MICROPROCESSORS IN ADVANCED SIGNALLING AND CONTROL SYSTEM DESIGN

Moderator: *John H. Auer, Jr., Manager of Advanced Engineering, General Railway Signal Co.*
Panel Members:
W. Terry Davis, Supervisor/Software Systems, Union Switch and Signal
Walter Friesen, Manager of Engineering, SEL, Canada
Michael J. Furniss, Senior Principal Scientific Officer, British Railways Board
Rainer Goetz, President, Studiengesellschaft Nahverkehr (SNV)
H.D. Hartkopf, Manager, Signalling Development Dept., Siemens Braunschweig
Ronald D. Kangas, Chief, Technology Dev., U.S. DOT/UMTA
R.W. Richardson, Manager, Electronic Systems, Westinghouse Electric Corp.
Henry C. Sibley, Consulting Research Engineer, General Railway Signal Co.

Following its introduction more than twelve years ago, the microprocessor began to see almost immediate application to non-vital railway signalling functions. Its use in safety-related applications, however, had to await the development of acceptable techniques for assuring system safety under conditions of failure. In recent years considerable efforts in many locations throughout the world have been directed toward just such developments. We now find a number of vital microprocessor-based systems and products in service and many more just around the corner.

Seven members, each of whom is well-qualified to discuss the application of digital processors to vital functions will sit on this panel. They represent a diversified group of methods and techniques for assuring safe-side results under conditions of failure.

This panel session will provide the opportunity to see answers to your questions about the use of microprocessors in safety-related applications.

Mr. AUER:

To begin, I would like to say "Good Morning, Ladies and Gentlemen," or is it Lady and Gentlemen. This is Session 5A, Rail Panel I. The subject is Microprocessors in Advanced Signalling and Control System Design. My name is Jack Auer, and I will be serving as the Panel Moderator this morning.

This morning's panel is made up of eight (8) persons each of whom is well qualified to discuss the application of digital processors to vital functions. The Panel members represent six (6) organizations that sponsored safety-related papers and we just concluded Session 4A. I would like to introduce the Panel at this time. Kindly hold your applause until all of them are introduced.

Starting on your left, we have Terry Davis who is the Supervisor of Software Systems, Union Switch & Signal Division for American Standard, from Swissvale, Pennsylvania. Next to him, Roger Friesen, Manager of Engineering, SEL, Canada, who comes to us from Toronto. On his left, Ray Richardson, who is Manager of Electronic Design at the Transportation Division of Westinghouse Electric, and he comes from West Mifflin, Pennsylvania. And on my direct right, Michael Furniss, Senior Principal Scientific Officer from the R & D Division of British Rail. Mike comes from Derby, England. On my immediate left, Henry Sibley, Consulting Research Engineer, from General Railway Signal Company in Rochester, New York. On his left, Rainer Goetz who is President of SNV. Rainer comes all the way from Hamburg, West Germany. And on his left is Hans Otto Hartkopf who is head of the Development Division of Electronic Interlocking at Siemens in Braunschweig, West Germany. And on my far left, Ronald Kangas, Chief of the Technology Development Division of UMTA in Washington, D.C.

Ladies and Gentlemen, let's welcome the distinguished Panel with a round of applause. I was very pleased when Lou Frasco, symposium technical advisor, asked me if I would moderate a panel on the subject of "Microprocessors in Advanced Signalling and Control System Design". Following its introduction more than twelve (12) years ago, the microprocessor began to see almost immediate application to vital railway signalling functions. Its use in safety-related applications, however, had to await the development of acceptable techniques for showing systems safety under the conditions of failure.

In recent years, considerable efforts in many locations throughout the world have been directed toward just such developments. We now find a number of vital microprocessor-based systems and products in service and many more just around the corner. These are indeed exciting times in the evolution of the railroad signalling technology.

At the risk of over-simplifying a complex subject, I might suggest that the techniques being developed to apply microprocessors to safety-related functions seem to fit neatly into four groups. One microprocessor with one program, one microprocessor with two different programs, one microprocessor with the same program and multiple microprocessors different programs. Each group has its own features and advantages. Every organization involved in the development of new techniques seems to be promoting one or more of these groups. Some have shifted from one group to another as they have gained experience. I think it probable that each of the four groups will finally be found capable of successfully spawning techniques leading to conservative railway standards that have been achieved with relay based systems. However, some of these groups may be found to have preferable features. Much of the excitement of the current railway signal environment relates to the debates that arise out of these alternatives.

I suspect that many of the questions that you have posed to our panelists will also relate to these alternatives. The second consideration that is being brought to the forefront by new development efforts is the probablistic characteristic of microprocessor-based systems. Whereas vital relay signalling technology has been traditionally based on the fail-safe principle, technicians developing microprocessorbased systems are accepting the existence of very small, but nevertheless non-zero probabilities of wrong-side failure.

Does this mean that the new systems are less safe than the old ones? Does it mean that the old ones are not as safe as we thought? Does it mean that the fail-safe principle is on the way out? There is a strong body of support for a No answer to all three (3) questions. I suggest that much of the excitement that has occurred throughout the railway system environment is related to this consideration and it is likely that some of your questions will be similarly related.

A few words on the logistics of the Panel session will be in order. Each member of the Panel will present an opening statement. Then I will present pre-submitted questions and at the end of the meeting, I will accept questions from the floor.

In an effort to answer as many of the unanswered questions as possible, and in fairness to all of the Panel members, I have asked each panelist to observe time limits. Up to two minutes have been allocated for each opening statement. The specific panelist to whom a question has been directed will be expected to respond in two minutes or less. Then each of the other panel members who indicate an interest in commenting on the same question will be expected to confine his comments to one (1) minute. For questions not specifically directed, I will give up to one minute to each panelist who indicates a desire to respond.

Now, I would like to have the panelists present their opening statements, and we will start with Terry and will go straight across.

TERRY DAVIS:

Union Switch and Signal's approach to vital micro- processors has been through the single microprocessor approach, using a dual path programming technique with dual paths -- one being the operational software and the other path being the diagnostic software. In most concepts, we're developing our safety around the same general guidelines as the relay-based systems, about one unsafe failure in 10^7 hours.

MR. AUER:

Thank you. Walter?

MR. FRIESEN:

Safety in systems is always provided by one of two methods -- one is a very high integrity designer/manufacturing process which results or guarantees a safety/failure criteria for the device or system, and the other is redundancy of one form or another. And that redundancy can either be serial, parallel or any other form. It must exist, however, in order to diversify the responsibility for safety in the system.

MR. AUER:

Ray?

MR. RICHARDSON:

The Westinghouse Transportation Division uses the check redundant microprocessor approach on its vehicle safety. Included in this is the analysis, by internal and external authorities of the safety of the system.

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MR. AUER: Mike?

MR. FURNISS:

Solid-state interlocking was developed by the Research Department of British Rails, that is, the software design and the hardware circuits. It is then being packaged and engineered by two companies in parallel, GEC and Westinghouse in England, and they are then going to manufacture and produce the equipment; in the first stage for a pilot scheme at Leamington Spa in the English Midlands and after that, they are -- or should I say for the pilot scheme the S & T Department of British Rail is responsible for validation of the program and general safety of the system. And it is hoped, at the successful conclusion of the pilot scheme that the system will be made available more widely in Britain and elsewhere, if required.

MR. AUER:

Thank you. Henry?

MR. SIBLEY:

The railroads and their suppliers have developed increasingly effective methods for operating trains efficiently and safely. They have applied new technology as these new technologies have become available, always maintaining a high level of safety that existed before the change. I find it exciting to be present as railway signalling enters the world of processor-based safety systems. We are facing new challenges similar to those met by the earlier pioneers in our field. Safety has been maintained through the earlier progressions because traditional techniques have been retained and adapted for use in implementing the new designs. Each step of the evolution was taken with confidence because some of the elements of the previous level were used to enforce safety at the new level. Mechanical design features were carried into vital relays and vital relays were used at critical points in electronic systems and design techniques used in the earlier systems are now being used in fail/safe processor systems. A most important feature of safety system design, which has been retained at all stages of evolution, is the team effort of designer and design reviewer or checker. After a system has been completed by the designer, the design is analyzed for safety and the results are thoroughly documented. The reviewer then checks the analysis and the design itself. Processor-based systems are not only designed with the designer/reviewer procedure, but with the flexibility of the processor, the function of the checker is designed into the system so that now checking is an ongoing process.

MR. AUER:

Thank you. Rainier?

MR. GOETZ:

Everybody is aware that one hundred percent (100%) safety is not possible in a working transportation system. More safety normally means higher costs. The goal must be to keep at minimum the safety status of existing systems if new technology is employed. Necessary it is now to find accepted state-of-the-art standards and methods to define the system as being safe for operation.

MR. AUER:

Thank you. Hans?

MR. HARTKOPF:

Siemens microcomputer systems, especially developed by Siemens for fail-safe operation, are so designed that every conceivable hardware failure affects immediate termination of further data processing. Therefore, no false commands can be transmitted. Some SIMIS features are a dual channeled microcomputer system, strictly synchronized operation, hardware comparators for all bus signals, failure detection capabilities in micro second range, identical hardware and software in both channels, variable size of memory capacity and peripheral equipment. Already, the first systems of the new Siemens design interlocking generation which is based on the sectional control principle using the SIMIS based microcomputer system are installed or are in real operation. Thank you.

MR. AUER:

Thank you. Ron?

MR. KANGAS:

I am here today representing both Lloyd Murphy who is from our office of Safety and Security and our own office. We are undertaking an initiative, at the request of the American Public Transit Association, to provide assistance to the transit authorities and to the industry, as a whole, to look into the issue of microprocessors. Specifically, APTA and many of its members have approached us regarding some of the issues and questions which have been raised in this morning's session and probably will be raised here. The issues that we are going to try to deal with in this upcoming year, and as we get together, looking at the policy-level aspects of how one handles some of the proprietary aspects of supplier software programs that go into the coding, issues of how one approaches the safety analysis, looking at the issues of reliability, maintain ability, EMI and EMC.

You will be hearing more about this program from both our office as well as through American Public Transit Association.

MR. AUER:

Thank you very much, gentlemen. We are indebted to Nabil Ghaly, a subdivision engineer from the New York City Transit Authority for submitting a list of six (6) questions to be answered by the Panel. I was very thankful to have them because up until about one hour ago, I had none of these cards submitted. But, now we have about five (5) so -- we will be using some of Nabil's questions, but not all of them.

The first question that I would like to put to the Panel, and these are not directed to anybody in particular, so we will accept volunteers and give every Panel member a chance to respond. The first question is this -- If redundancy, software or hardware, is used to achieve fail-safe operation, is the system then less reliable due to the introduced redundancy or is the system also fault-tolerant? Who would like to take a crack at that?

MR. FURNISS:

The way in which we tackle this -- of course, if you use redundancy in hardware, as we do at the track-side, for instance, we potentially are going to lose a lot of the availability of a single processor system. At the track-side, I dare say, many people will disagree with me, it is not quite so important if you have a failure because in many cases this is only going to be one signal, one set of points that is out of use. Bad enough as that may be. It's certainly not as bad as a central interlocking failure where when you triplicate a system, two (2) out of the three (3) modules must be in working order for this system to be able to operate at all. And in this way we are able to get very high availability of the system. One failure -- one complete failure of the system every 250 years, is what we're talking about. We shouldn't experience complete failure in interlockings, we hope.

MR. AUER:

Thank you, Mike. Anybody else interested in responding to that question?

MR. RICHARDSON:

There seems to be -- I guess, really a fundamental thing that's being asked. If I add redundancy to get another pathway in which things can work, then I think of reliability in a system. But in this safety thing, you add the redundancy to give a checking so that either channel could shut down the system so, essentially in the mathematics, you would lose some reliability in this system. Whether you are introducing redundancy to get another pathway to work or you are introducing another pathway where you can shut down, one way you pick-up reliability -- the other way you lose.

MR. AUER:

Thank you.

MR. SIBLEY:

I would like to mention a discussion we had many years ago when we were trying to establish -- document our approach to safety and we wrestled with this word "redundancy" and redundancy strickly means more than is necessary. If you have something that is redundant, you can do without it. We have chosen the word "diversity" to indicate the use of a second or additional independent channels that must all agree in order for the output to be acceptable. So you talk about diversity as a way of increasing the safety of the system and if, because of all of the various considerations, we have a question of availability, then we talk about redundancy, putting in additional systems anyone of which will do the job safely.

Now, as far as the hardware is concerned, generally if there is special interface hardware required outside of the processor, that is designed along the same fail/safe principles that we have used for hardware in earlier systems.

MR. AUER:

Okay. Terry.

MR. DAVIS:

We, at Union Switch and Signal, have been using the single microprocessor approach, but still haven't ignored the reliability problems. We would want to have a higher system availability and the way we accomplished that is with a hot stand-by computer. It is not in redundancy for fail-safety but in redundancy for reliability. We have a second channel, a second whole computer system which winds up controlling the interlocking should the primary system fail. Either system itself could completely control the interlocking safely, so a single failure won't shut down our system either.

MR. AUER:

Anyone else who wishes to respond to that? Then the next question I would like to ask is also from Mr. Ghaly of the NYCTA. Is the safety of the system dependent on some critical elements and, if yes, is that desirable? Who would like to tackle that? Roger?

MR. FRIESEN:

I think the question of safety and critical elements is one that maybe needs a bit of redefinition. Maybe, I don't fully understand the question. However, I would say that in any system, that we have in signalling operation right now, safety of the system, is dependent on a single element. A vital relay is counted on to do what it should do or you have either a reliability problem or wrong-side failure which is a rare event, but nevertheless could happen. So, what we really have to talk about is the overall reliability of that single event with respect to a mean time between hazard of the event. An analogy that I guess one could throw out is if you have two vital relays on a track circuit, let's say, and one of them drops and the other one doesn't, what do you do? It's the kind of thing that puts you into a dilemma that you would rather not want to answer that question because it should be a fail-safe relay.

On the other hand, you can thereby create yourself reliability improvements in terms of service reliability if you chose to use the route of redundant paths, of vital systems which can then operate in parallel in order to provide a higher service reliability in case one of them in fact fails.

MR. AUER:

Thank you. Any other comments?

MR. SIBLEY:

In the tradition of carrying forward the elements that we have relied upon for safety in the past, once again, in all of these later systems, we have always gone back to the critical element of the vital relay, brought along as the final arbiter.

In the case of the processor-based systems, we have between the primary logic and the vital relay we have the vital driver and that has to be a stand-alone safe design that is going to depend upon the relay as the final arbiter of its behavior. Is this desirable? I feel it is desirable from the standpoint that we can put a large amount of attention into the design of this critical element such as the vital driver. We can have many man-months, if necessary, of safety analysis to convince ourselves that it's okay and that same vital driver is then going to be usable for all kinds of different systems, no matter what the primary logic may be.

MR. AUER:

Any other comments? I think I will combine two (2) of Nabil's questions in order to get to some of the other questions here. These are -- Do you always specify false as a safe failure mode? And, secondly, how do you ensure the integrity of a function and its complement? Who would like to tackle that? It's a tough question, Nabil.

MR. DAVIS:

Well, the first one's easy. It is always false or zero as a safe output. Whenever we detect any type of failure in our computer system, the ultimate for us is to stop the delivery of the vital output power to the output devices. This causes all outputs to fail under safe conditions, a dark signal or a switch not moving. So the answer is Yes to the first one. And, in terms of how do we ensure the integrity of the function and its complement, it is basically the dual path programming techniques that we use. The function is actually the first of the dual paths, meaning the operational software where we perform the function. And then the complement for us, of that function, is not merely the inverse but the complete diagnostic path, verifying both the hardware and the software integrity of the system. It is a little bit more complicated than just merely a complement. It's the complete diagnostic package with the wrap-around techniques that we discussed earlier.

MR. AUER:

Thank you, Terry. Anyone else?

MR. RICHARDSON:

On the first one, I take falses -- do you always specify falses as a safe-failure mode? Essentially the false is the lower energy, the gravity dropout, or a signal that was oscillating that goes away. Yes, you want to take the lower energy thing as the failure mode. How do you ensure the integrity of a function? This goes over a broad range. The original integrity, through testing for verification -- once a system is operating, how do you ensure that something is working? We're using some built-in test features. When signals are not available during normal running, we can inject signals to be able to run some built-in tests to verify things. If the equipment has been turned off, when you first turn it back on, a wake-up test can be done to verify the integrity of the safety elements.

Finally, the periodic maintenance, where an overall verification of the system is programmed in all systems.

MR. AUER:

Thank you, Ray. Anyone else?

MR. SIBLEY:

I think the definition of false and true are a matter of how you assign these terms to something, just the same as we have always had the problem of positive logic and negative logic and ors and ands and nors and nands. I don't quite know how to answer that. In the case of an input with VPI with an input that is on, we consider that to be the true state and when we're looking at the output, then we're concerned about an output being on when we don't want it on, so we sort of have to stand on our heads when you get to the other end of the system.

Ensuring integrity of a function and its complement -- I am assuming that complement as meaning the diverse expression of that function. We ensure the integrity when we're at the actual hardware level, when you're outside, for instance, looking at contacts on vital relays, we ensure the integrity at that point by using vital circuits. Once we get into the processor and we're handling this now as a bunch of bits, then we go to diverse paths and in completely separate, diverse ways, we get the expression of that function and then after the processing is over, those two expressions must agree.

MR. HARTKOPF:

For microcomputer call, the memory -- the program memory, I think is always a safe failure. The interport or outerport must not be a fail-safe failure.

MR. AUER:

Thank you. Any others? Roger?

MR. FRIESEN:

The question relating to false data, I guess, in logic systems, electronic logic systems, software systems, is probably a little bit of a misnomer since a false-state is any state that isn't any way you wanted it, rather than a false-state in the sense of an assertive or negative condition on a logical factor. So, from a safety point of view, you have to rationalize that a false-state therefore is the failure rate of the device, whatever that may or may not be. And so, a false-state, then, has to be that rate you have to evaluate in the hazards analysis which is the device failure rate.

On the software side, a false-state is a logical output that is unexpected. Again, only through diverse paths of processing, either multiple computers or multiple programs can that false-state be identified. So the fundamental rules will continue to apply.

As far as the integrity of the system is concerned, I think, again, if you apply the same rules, you can always come back to the fundamentals of multiple entities -- of redundancy, diversification. If you want to know a switch status and you want to know it more precisely, then you use nonvalent bits in a message transmission in order to ensure that both ones or both zeroes are unacceptable states. If you expect a one and a zero as a pair, in one way or another, in order to know that the switch is either normal or reversed, and the integrity is assured through redundancy once more, through redundancy of the same information in two separate bits.

MR. AUER:

Thank you, Walter. Any others?

This question is from Dave Mitchell from Batelle. One of the attractive attributes of micro-processor systems is the ease of making changes. How do the ATC suppliers plan to maintain the integrity of the software from a safety standpoint or will this be the responsibility of the Transit Authority? Who would like to tackle that one? Terry.

MR. DAVIS:

The approach that we're taking is similar to the others we're discussing here, being one base executive software that resides in every system no matter what the geographical constraints are. And then the set of Boolean rules that we basically map directly from the old relay diagrams that have proven, throughout history, to have the correct Boolean algebra contained in them. And once the software is proven to be the same as the relay diagram that has been used, as a typical circuit for the past history, we feel that the interlocking software then will be safe in its inate state. That is the history of the past. The old relay systems of the past will still be used in the microprocessor systems of today.

Q. Doesn't answer question. Who has ultimate responsibility? The supplier or transit operator?

A. If the supplier is doing the final programming, absolutely, the supplier would be. The same as with the relay based systems, the supplier installs them and they will also be responsible for their stages.

If the Authority winds up making their own changes, putting in their own types of circuitry, then ultimate responsibility would, I suppose, have to rest with them. With our system, they could be done either way, with the high-level language compiler that's been discussed. Does that answer the question?

MR. AUER:

Does someone else care to comment?

MR. FURNISS:

The changes on British Rail are traditionally made on large schemes by the contractors, but for small changes, British Rail would expect to do them themselves in their design offices. And this kind of method is being maintained with the new technology. And therefore, design offices will be equipped with equipment for being able to prepare data and to compile it and to load the PROMS and, subsequently to check it as well. Also, design offices are being equipped with a simulator which I showed you in the slide, as well, so they can do all the testing that is necessary for the particular layout change.

MR. AUER:

Thank you, Mike. Walter?

MR. FRIESEN:

I always have this problem with the idea that because it's software it's easily changeable, and therefore, how do you control it? I think that's a mental problem that people have. Yes, software is easily changeable but so is a wire on a relay easily changeable. The point is that changes have to be made difficult enough with enough control process that it becomes the equivalent of the control process that you have on any hardware system when you go through a change. The impacts of making that change on the operation of a railroad are much, much less because it can be implemented much quicker and that's where the real benefit comes in, not from the fact that you can change it continuously and easily. So the process of the change, the integrity for the change has to be equal to what has been done for any hardware changes where the change is designed, it's tested, it's bench-checked, it's been simulated, then it's been implemented in the field and then goes through an operating check. Those steps cannot be avoided. The responsibility for the software that is in there has to rest with the person that puts it in, and I think that's sort of a bottom-line that can't be avoided.

MR. AUER:

Thank you. Anyone else? This question is from Mr. Runsey I believe, from Metro Canada. The discussion on transit EMC -- the discussions on transit EMC -- have tended to concentrate on the effect of vehicle-generated propulsion interference on wayside signalling telecommunications equipment. However, given the increased use of electronics and microcomputers on board transit vehicles, can the panel comment on their experience with respect to the susceptibility of this equipment to both the vehicle -- generated interference and also to the general levels of radiated RF interference that can be anticipated in an urban environment? What studies have been applied in design of such equipment? Who would like to answer that question? Ray?

MR. RICHARDSON:

Okay, there seems to be about four (4) questions, or so, in there. We use microprocessors in the vehicle environment, a lot in the people-mover systems. We take pains to test and try to look for any interference in using good design practices. We look at the type of noise environment we get from our substations and from the propulsion equipment and try to make sure the frequency allocations are such that there won't be interference, and a lot of the people -- mover environments are a little more clean, in some sense, with regard -- usually in airports you do have radar but we use a dedicated guideway. The downtown people movers, we're just getting into, so there will be some exposure between us interfering with the outside world and the outside world interfering with us. But, again, we try to use good design practices to get away from that.

MR. AUER:

Thank you. Anyone else? Walter?

A. EMI, in the transit environment has been a real problem and I think what I want to do is add a problem more to it than to answer it. However, I will add some answers to the question. And the problem really is one that if you say you were to do a site survey, at the start of the installation and establish what levels of radiation you have that you have to survive through the susceptibility point of view, then you design for that and install the system and say it works and you certify it. A year later there is going to be a 50,000-watt radio transmitter that is installed a mile away from the track. And so -- you have this problem that the environment changes so that the design has to be toward the worst case environment that might be definable and that's really where the difficulty comes in. How can you define that worst-case environment? In the case of our onboard equipment, we design to 140-db microvolt per meter level of radiation that the system might be subjected to. The question that remains -- is that the correct value? Or should it be a different value? I don't know. I'm very interested, as well, in terms of what values are used in terms of defining the susceptibility that onboard equipment might have to survive through.

There are a lot of good design practices that one takes into consideration, in putting the mobile equipment in place, various grounding and shielding techniques, double-buffering and isolation techniques. At some point of radiation, all of those techniques are going to fail. And the question, at that point, comes in -- How do you deal with those things? Natural reaction is that they must be safe. Yet, I think it could be generally accepted that if we took a line circuit vital relay arrangement and subjected it to enough EMI, that relay might well not drop and to me, that's where the onboard dilemma is because we don't control the environment very closely although it is somewhat controlled. I haven't any answer to the question, but I have added some additional considerations in to that whole situation which is, I think, fairly well undefined at this point, and it needs definition quite baldly.

MR. AUER:

Thank you, Walter. Hans?

MR. HARTKOPF:

Protection against electrical interference for those where construction is used for protection, the currents on the power supply line, are suppressed by using interference processor filters. Very few cables are used for connecting the peripheral units. The cable connection to the input and to the output ports is isolated both electrically and physically from the electronic circuits.

MR. AUER:

Thank you. Anyone else? This is a very interesting question from Mr. King of Batelle. What do you see as the largest barrier to the widespread application of microprocessors in transit safety systems? Who would like to tackle that one? Rainer.

MR. GOETZ:

In our country, we have federal regulations for all the things related to safety in transit and there are well installed processes with the conventional safety means and there are procedures how to secure this system. And I think that in our country, the main barrier is to bring this -- these new systems -- this new technology through this procedure. I just want to mention fail-safe as the principle that underlies everything we have in our country, and there is no system coming through just by probability. Probability is no means of coming through the process to be installed as a the safety system, and so what I mentioned first -- we need standards. How much safety do we need? And, second, we need how to secure this safety we ask for in the systems. And I think this barrier has to be overcome just by those people here in the room and outside, the specialists, who define the state-of-the-art. State-of-the-art of safety.

MR. AUER:

Thank you, Rainer. Terry.

MR. DAVIS:

The problem first is really defining it, as he just said. The second problem is -- how do you evaluate it? In the relay-based system, we have the history of the past, once again, that shows us statistically how many unsafe failures we have had over a given amount of time. With the new microprocessor-based systems, it is very difficult to begin to guess about how often things are going to happen and how many failures are going to cause unsafe failures. This, I think, is one of the biggest hurdles to overcome -- it's how you prove what the safety ultimately is; although these systems will be safe, how do you begin to prove it, if not through time?

MR. AUER:

Thank you. Ron?

A. I'll try to give some of the answers to the question in relationship to what individuals talk to me about. Since we don't buy those kinds of systems so I can't always answer. One of the concerns that has been expressed to me is the issue of the changing technology. As we move down the pipe -- ten (10) or fifteen (15) years, with the availability of replacement parts, where is that technology moving? The issue of safety was raised relative to developing the level of confidence which both the buyer and seller have in being able to have on the system when they buy it? The issue of cost -- I think, is also a question in many minds. Can we assure that, from a capital standpoint and long-term maintenance standpoint, that what we are going to get into is really cost-effective? Those are questions that have been raised. And the other issue, I think, is on flexibility in terms of microprocessors. What am I getting? How flexible is it? Will I be able to improve throughput productivity through the use of microprocessors and, if so, how? I think those are some of the questions that have been expressed to me.

MR. AUER:

Thank you, Ron. Mike?

MR. FURNISS:

The barriers that we have come across have progressed as the years have gone by as we have been into this now for quite a few years. First, perhaps was to attract people's attention to the fact that they really need it to be able to save money. They needed the system, not just to introduce electronics, but to save money. We then found that people were very frightened about the safety of the system and we had to go through a lot of time and convince ourselves, and convince them that we could produce something of an accepted level of safety; i.e., the same or better, than what you have at the moment with relay circuitry. We then went on to the problem of maintenance. With the signal engineers on the ground -- the ones who help to maintain the equipment on the side of the track. Would they be able to cope with this? This was achieved by making the equipment modular, in modules, in fixed boxes, so all they had to do is to be able to diagnose which box is faulty and change that. The second -- line maintenance in workshop, we could afford then to have a higher standard of expertise and be able to take modules to pieces and find out what really the problem is.

We have now gone on, perhaps up to the stage where we are at the moment. We're now going on to people thinking --- Well, it's really going to save money and if it's going to be so easy to maintain, can we have it quickly? And I think now we're going through the phase, in Britain, at least, that everybody wants it now, and what on earth are we messing around for? We're talking now on British Rail of having something like eighteen (18) months trial, starting now and they're really not prepared to wait until then.

MR. AUER:

Thank you. Anyone else? This question is from David Turner, from Booz, Allen, & Hamilton. Two parts. One -- What safety impact in failure possibilities of the microprocessor do you allow for in the design of vital equipment. And, two -- please discuss the microprocessor worst-case failures in context of equipment design choice of one versus two or more microprocessors. Who would like to tackle that? What safety impact of the failure possibilities of the microprocessor is allowed for in the design of vital equipment? Mike.

MR. FURNISS:

I'll have a go at it. I don't really understand the question. But I am sure you can't rely on the microprocessor to really do anything and be sure about it. It could fail, the outputs could fail, high, low. There could be timing failures, just about anything could happen. And we have to allow for that in the design. We do it by having either two out of two in our case, or two out of three; although we have seen other people use a single processor system and they have a quite reasonable, you know, justification for doing this. I can only talk about the two out of two or two out of three systems. So we allow more or less any kind of failure of the actual microprocessor concerned to do this.

The idea of two out of three is purely to get availability out of the system and not an increase in safety, of course. You can maintain the same safety -- get a better availability.

MR. AUER:

Thank you. Anyone else?

MR. TURNER (audience):

Mr. Auer, may I amplify that and direct it in particular to Mr. Davis or Mr. Sibley?

MR. AUER:

Yes.

MR. TURNER:

In particular, I would like some clarification on -- following Mr. Furniss' notion that microprocessors can fail in any way, that we can't rule out particular types of failures in the microprocessors, what specific techniques are used in the design of a single processor system to ensure that extremely perverse failures of the processor cannot result in unsafe failures? In particular, imagine the failure of a micro-code store of a microprocessor that causes it to continue to issue its normal set of safety assurance outputs and watch-dog outputs, but behave irregularly in its safety-direct output?

MR. DAVIS:

We basically, in the single microprocessor approach, build the code in RAM that performs the vital output which is input to the vital power supply, supplying output power to the devices that control the switchpoints and the signals. Should any failure in the microprocessor occur, the program code wouldn't even be in existence because it is destroyed upon execution. It won't even be in existence to produce that particular output; therefore, if a vital -- if a tight timing window that the output needs to be produced in, as well as the complicated pattern, which is to say that unless that is produced, no output is generated for the output devices. Of course, you could come up with some very remote specific set of possibilities where it could produce that particular output but we believe that that possibility is one chance in our fail-safe criteria of one chance in eleven hundred (1,100) years. It could happen, but for a very small probability.

MR. TURNER:

I understand, then, that there is a quantification of perverse failure probability involved in the design of the single processor system.

MR DAVIS:

Absolutely. As with vital relays. They can fail unsafely; it is a low probability but they can do it.

MR. SIBLEY:

I think that you can see a commonality of approach from the American Signal Companies, I think it has to do with our carrying on the thinking that has gone on in relay circuit design and you find that some of the things that each of us is talking about are very similar. We also require that the vital driver operate from a program that does not exist until the primary -- the main processor -- the primary logic has developed that program and the vital processor cannot operate on that program unless it destroys it, and it does. So, we do not have the chance of a vital driver processor making a lucky jump into some part of memory and running an output program because it doesn't exist. We try to design the entire system with our approach. We force the designer to recognize -- to identify recognizable hazards and address safeguards to them and, as in the traditional approach, we have the design reviewer also looking and seeing whether the designer did his job. We also have the approach of verifying the critical tasks, verifying the critical conditions such as the states of outputs, looking at these things as program memory content and all of these various things and addressing tests to them that must be passed in order for this vital driver to have a program that it can run.

Now once again, recognizing that it is always possible for some order of any number of bits to come sliding into the processor on a moonbeam and this might cause something to happen, recognizing that there is that probabilistic sense -- aspect of the thing. We make that number of bits so large that we're trying to match this goal with relays and any of you that were here this morning -- I guess I misspoke, with something like an unsafe failure in a hundred (100) years and I think the often quoted figure is an unsafe failure in a million years.

MR. TURNER (audience):

I think that the real challenge will be the quantification of those moonbeam shots that you refer to in single processor systems. I personally believe that the challenge is much greater in that design configuration.

MR. SIBLEY:

Well, we have found that some of the analyses that we have done, that by the time we have satisfied a criterion for nuisance failures that the very-much-larger criterion for unsafe failure has naturally fallen out of those numbers that we put in there. We found that the nuisance failures, in some cases, to be a more difficult thing to achieve.

MR. AUER:

Could you please use the microphone?

MR. WALLER (GEC General Signals, UK):

I just wonder, although it does not affect the systems with which I'm personally concerned, whether the last questioner could quantify his experience or say what it is that enables him to say "I'm not sure that what you're saying is right." Or is this, shall we say, typical of the major barrier to getting these systems accepted. Those who are working in this field know the problems because we are living with them all the time. We know that one day something is going to go wrong -- and somebody is going to say, "What went wrong?" and you have to say, "Well, it won't happen again for a million years." There are all those sort of questions going on in our minds. But it does sound as though the last questioner has something positive, that he believes certain things can come down on a moonbeam and get into micros. Has he got any real basis for his question, or is it just a worry? Because that is the thing that we have to contend with -- the worriers who have not spent the time looking at the details. Those of us who are involved in the details have got to perhaps explain ourselves better. Those who are worrying must place some faith in people because it is what we are having to do. Thank you.

MR. AUER:

Thank you, sir.

NEAL BRUMBERGER (BART ATC):

I'd like to respond to that because a lot of what Dave mentioned is the result of the work he is doing for me and yes, we do get into the details, and we understand the details, I think, very well. The problem is this -- that in a large complex device like a large-scale integrated circuit, it is impossible to define all the different kinds of failure modes that can occur. As a matter of fact, there was one fundamental principle that we have used in the past in designing a fail-safe or vital system with discrete components and a discrete component can be a fail-safe relay or it can be a transistor or a capacitor, or whatever, which no longer applies. It is very fundamental. Every failure mode and effects analysis or circuit analysis of an interlocking circuit makes one very important assumption in assessing the safety of the system. That assumption is that the connectivity of the system doesn't change. Okay? Wires don't magically move. Components don't magically shift their position on boards. The connectivity of the system does not change. Okay? The failure modes of large-scale integrated circuits are exactly the opposite. The internal connectivity, and processing that those circuits do, under failure conditions, does change and so the old techniques don't apply any more. Many of them will simply fail. What we're trying to get at here is how is a supplier going to come forth and present his design criteria and his analytical methodologies in sufficient detail and in sufficient specific objective criteria established so that a reasonable assessment of safety can be made. Because the words "fail-safe" don't work any more. They really don't. And I think, Rainer, that is going to be one of the biggest problems, is that the total, absolute black-or-white system -- a system is either safe or it's not safe -- concepts won't work. And we all don't have enough time to sit around and wait for another 150 years to decide if these technologies prove out to be good or not. We need methods which can predict, on a reasonable basis, what those expected safety levels are going to be, socially we need to establish those levels and then set those criteria and develop an analytical methodology which allows us to measure, in an objective way -- not a subjective way -- an objective way -- whether that criteria has been met.

We have tried that at BART and we're working that process now and I think that's what the thrust of most of these questions is really about. Not whether or not one particular design approach is going to be good enough, or not, but rather what are the consequences of the different approaches in terms of setting those criteria and then objectively demonstrating that they have been met.

MR. AUER:

We have more of the audience on the panel than we have on the panel.

MR. BISSETT:

I'm Kendrick Bissett, and I'm with the Chicago Transit Authority. And Dave (Turner) and I were having a little discussion earlier on about some of the philosophies that you people are using and I'm very intrigued by some of the responses and questions that are being raised here, in particular with regard to the kind of safety analysis that our friends here from California are looking at. And I think that Mr. Waller came up with the correct answer a bit earlier on.

I am responsible for the signalling on an operating property and I have already indicated to several of the suppliers that I am anxious to get one of these solid-state microprocessors on our property and see what it does. I am quite convinced that it's not going to take 150 years to find out if these systems are "safe enough." I think that the analysis of this -- the testing of these systems over a fairly short period of time will give us a fairly good idea of whether they can be expected to be made safe enough for our use on our transit properties.

This analysis, however, can't take place until such time as we get some of them out here and somebody is going to have to bite the bullet and say "Okay, we're going to trust the suppliers," that they have done ungodly man-years of work in developing a safe microprocessor-based interlocking -- man-years which I can't afford to spend on my property. I don't have that many people to be able to do it. I can't afford to spend the money unless Ron (Ron Kangas, UMTA) is willing to support a major effort. I don't have the money available to hire a consultant and, to be perfectly honest, there are few of those I will trust any more than the signal suppliers. I'm sorry, Dave, but -- As I see the light, I think that the net answer on all of this is whether we -- the properties -- the Federal Governments in various countries, and whatever other regulatory bodies there are, agree and are prepared to explore this kind of technology. We are going to have to try it out, see how it works, because no matter how many reams and reams of paper and charts and statistics come out, I honestly don't think that's going to make a bloody bit of difference in how reliable and how safe the system is. Thank you.

MR. AUER:

Thank you very much. Mike?

MR. FURNISS:

Yes, I can sympathize with you wanting to see the system operating on your own bit of territory. On British Rail we see this as an ongoing process, a trust, in getting experience. In the first case, we've got to make sure that the safety is sufficiently high, to be able to go on with the project. That's the main thing at risk, just to go on with the project. And, in order to do this, we must make an assessment all the way through because when we have a piece of equipment, and it's been running for twenty (20) years or so, we've really got to have the analysis, the original analysis that we had and the ones that we're making at that time -- in twenty (20) years time -- to be able to see what we in actual fact have done, so that we can make a proper assessment of the system.

It's a question of going on from trust-to-trust and we are only taking quite small stages in works, and the biggest stage, I suppose, is when you run a passenger train over the system, which we haven't done yet, but at least we will, at that time, have had something like eighteen (18) months of experience, the last six months being very, very dedicated experience of the system, being fully monitored so that we can have some clear certainty that it is going to be all right. But I certainly can sympathize with you wanting a system, to be able to see it, and that's what British Rail wanted as well.

MR. AUER:

Thank you, Mike. Mr. Smith?

MR. SMITH:

Mr. Chairman, the name is Victor Smith and I'm the Director of Signalling for London Transport. Back home we are currently installing a computer-based interlocking, and I trust it is going to work well, and I trust the staff back home is working on it. But it's not that I want to talk about. I was going to make a suggestion and I'd like the panel's view as to my point of view. We've talked a lot this morning about wrong-side failures -- in fact, we've concentrated on that, and I think quite rightly so because they're important. But, gentlemen, if one reads accident reports, and I do, and I suspect many in this room do, I can't think -- and I've been trying to recall one, sitting here -- of an accident that occurred because of a wrong- side failure. Now, wrong-side failures occur in all systems, but I can't think of an accident, not just off-hand -- perhaps somebody will tell me over lunch of one. Most accidents occur because you've had a right-side failure and because you have the right-side failure, you bring the train to a stand, and then our operating friends -- they can't wait -- they're impatient. They want to move the train and lo and behold you have a disaster on your hands.

Now, gentlemen, if you produce a microprocessor-based interlocking, and you do it a lot cheaper, and we can have redundancy, or diversity, I think you called it. Therefore, when you get a failure, we can keep the trains running under signal and control. I'm going to suggest -- and that's where I'd like your view -- we have produced a far-safer system than we have today. Thank you.

MR. AUER:

Thank you very much, Mr. Smith. I have a few more presubmitted questions, but I think we are getting near the end of the session and I think I should give you an opportunity to raise questions from the floor.

Q. I have a question on life-cycle costs. I'm not pretending to be an expert. I was wondering what the trade-offs were with the initial cost of a relay system and how long they will operate without failing, versus a microprocessor system and if one's cheaper than the other, to begin with. How many years one has to operate. We had some relays in New York that were put into service in 1930 or something like that, and they're still running. I'm just wondering what the -- where the crossover point is on money on life-cycle costs.

MR. AUER:

Who would like to answer that question? Terry?

MR. DAVIS:

It's a very difficult question to quantify, mainly because when you say you have relays that were put in in 1930 and are still going, I dare say they have been maintaining it. How much maintenance has gone into them is difficult to quantify as well. The microprocessor based systems should be initially cheaper to install than the relay-based systems, but there is no doubt that they will probably be life-cycle shorter. You won't find one installed today that will be running 150 years or 50 years from now. The parts probably won't be available for the maintenance. However, various steps are being taken by the suppliers to choose parts that have a high probability; again, probability of being around for a number of years. One of the ways we at Union Switch are doing that is we are trying to choose parts that the automotive industry is using. They are, by law, required to make parts available for ten (10) years from the date of purchase. So, we can at least verify to that level that parts will be around for the maintenance of them.

Beyond that, though, it is difficult to say much.

Q. Are these considered mil-spec parts?

A. Depending on the system requirements, yes. It is a system-dependent question. If the reliability that the customer or property wants requires mil-spec components, obviously that's a higher cost. However, you have to keep in mind that mil-spec components are only the same exact components that are put through temperature test and burn-in, so really, running your system for a while and letting it cycle through the high and the low, winds up giving you the security of a mil-spec component.

Q. (unintelligible remark)

A. With technology changing as rapidly as it is and prices on parts falling, you're going to wind up, for the same reasons you want to replace your relay system today with microprocessor equipment because it's cheaper, you'll want to replace today's microprocessors with tomorrow's equipment because it, again, will be cheaper.

MR. AUER:

Mike?

MR. FURNISS:

I think one should realize that microprocessors are changing and I know all those comments are true, but the thing is also you can design the system so that the modules are -- the interfaces between the modules are always the same and although the actual microprocessor in a particular module, the circuit board may have to be changed, it fits into the existing system so that you can maintain it for many, many years into the future.

MR. AUER:

Anyone else? Another question from the floor?

MARTY LUKES (Washington Metro):

I believe Dave and Neal addressed, with Westinghouse, what they are going through to personally satisfy themselves that the Westinghouse Train Control System is safe. Maybe each one of the manufacturers would like to propose how they anticipate satisfying us in general, as customers, how, during the design and implementation phase, that their system is, in fact, safe.

MR. AUER:

Who would like to start -- Walter?

MR. FRIESEN:

The question is one that probably requires a little bit of a difference in concept of philosophy of how both the suppliers and the users think and operate. In the sense that in the safety analysis is wrapped up, probably more than anywhere else, the fundamental key issues that are proprietary to your system as compared to somebody else's. Therefore, to publish them in a published document, for a user to read and review and study, becomes a real problem. What we have done so far, is to go through the techniques of how we do our safety analysis, how we ensure safety, and as a further step, then allow the user to review the safety analysis. However, we do not publish it out-of-house. In other words, the user would come to our location, our facility, and review the analysis that has been done. It does require, however, a very large confidence level on the part of the supplier and the user and that has to be established to the point where suppliers feel comfortable that the proprietary nature of their data will be preserved.

MR. AUER:

Someone else care to comment?

MR. SIBLEY:

I will. I should have been introduced this morning, as Jim Hoelscher threatened, as the former Henry Sibley, because I am retired from GRS and I cannot speak for them from a policy standpoint anyway, but I understand that GRS has the same policy -- that if a customer convinces them that they need to know and GRS feels they should be told, they establish this confidence, then they can sit down with the designers, with the engineers, with the reviewers, look at the documentation, and get the assurances, that we hope they are looking for.

MR. AUER:

I would like to take one last question -- from the gentleman in the back of the room. Sir, we're running out of time. Very quickly.

ALAN COTTON (Operations Director, Hong Kong Mass Transit):

I would just like to make a quick observation rather than ask a question. Backing up Vic Smith. Because in a very heavily trafficked, underground railway, the most important question, I believe, is its reliability. If, in fact, the service is brought to a stand by right-side failure, a hazard situation exists straight away. Crowds in the stations, up to 3,000 people in the train, especially where you are depending on air conditioning to keep for the environment tolerable. Therefore, I do think it is very, very important, that even right-side failures are restricted to a minimum. We had, I would have to say, one wrong-side failure in Hong Kong and that in fact was due to maintenance staff making the wrong connection. But it didn't, I'm happy to say, cause an accident.

MR. AUER:

Thank you very much for that comment. We have had a discussion of many very interesting elements or facets of vital microprocessors this morning. We've talked about reliability, critical elements, the effects of interference, system integrity, how do you make program changes, safety from not stopping as well as stopping the trains, minimizing all failures, life-cycle costs, convincing customers of safety.

Indeed, we are well into a very interesting and exciting new era in railway signalling. I would like to express my thanks to the Panel for their efforts this morning, and I would like to thank the members of the audience as well for their participation.

What I don't like to be called is late for dinner, and that's coming up, so I think we ought to adjourn. Thank you.

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Energy Recovery Technology

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ENERGY RECYCLING/REDUCTION
A TRANSIT OPERATOR'S PERSPECTIVE

J. D. Wilkins
New Jersey Transit
USA

In this period of scarce operating funds, transit agencies are always on the lookout for ways to reduce costs and improve productivity. In short, we are seeking a variety of means to improve our operating ratio. The ability to recycle or reduce the total amount of energy expended per unit of transit service provided is one avenue to be researched in this quest. At the present time, the total fuel consumption at NJ TRANSIT is approximately ___ percent of our total operating budget. The amount has grown significantly over the past decade and, thus, exerts a greater leverage on our total budget.

There are a number of avenues that can be reviewed to improve the amount of energy required for each unit of transportation service provided. These include:

1. Improve operating strategies to reduce the amount of energy required.
2. Improve existing technology associated with the diesel engine.
3. Electrify transit services.
4. Investigate state-of-the-art propulsion technology.

Let us take a more detailed look at each of these areas to determine what level of impact can possibly be achieved.

Improved Operating Strategies

The manner in which transportation systems are operated has a direct bearing on their energy efficiency. Let us look at a few areas that can be addressed to improve the amount of fuel consumed per unit of service consumed, the passenger mile:

1. Decrease Service Cycles - The average urban bus system is characterized by its stop and go nature. Diesel engines are constantly being subjected to cycles of acceleration and braking. A decrease in the number of these cycles would decrease fuel consumption and the amount of energy required to provide a passenger mile. The ways of achieving this reduction are several:

   - Increase the distance between bus stops - The national standard in this has been seven stops per mile although they are often much closer. The European standard is closer to four stops per mile. Adoption of a lower standard would decrease the number of service cycles and improve fuel efficiency.

   - Bus priorities - The establishment of exclusive right of ways, bus lanes and priority signal treatments will also reduce the number of service cycles.

   - Express service - The ability to segment a line and operate express service over a portion of it will also reduce service cycles. This type of service will also move average speeds towards more optimum fuel consumption levels and further add to fuel efficiency.

   The ability to take advantage of these options is very site specific. Few systems, since they handle a significant number of senior citizens, would be able to make a signficant reduction in the number of stops. Community response would not support this type of activity. The implementation of bus priority measure must contend with a labyrinth of institutional constraints. Transit agencies must negotiate with numerous highway or street departments, public interest groups and so forth to obtain such treatments. The fruits of these negotiations can have many positive impacts as witnessed by the Express Bus Lane which is used to access the Port Authority Bus Terminal in New York and the bus only lanes now in operation on Madison Avenue in the same city. The number of service cycles has been reduced and the rider is afforded a much faster service. The pay offs in this area can be very high and it should be investigated in great detail.

   The ability to operate express service is very site specific since many systems do not have the service density to support this type of service. NJ TRANSIT is fortunate to have a network of suburban commuter lines which can take advantage of heavy service densities and a system of express highways. The average speed on many of these routes varies between ___ MPH and ___ MPH. Average fuel consumption is about ___ gallons per passenger mile versus ___ per passenger mile on our urban transit routes.

2. Increase the Number of Passenger Miles Per Vehicle Mile -Transit systems should be scheduling their operations to optimize the number of passenger miles or, if you will, utilization. Like most urban transit operators, NJ TRANSIT schedules its urban service schedules to accommodate a load factor of 125 percent of a seated load at the point of maximum loading. We also limit the amount of standing time to about 10 to 15 minutes. Our express operations are scheduled to a load factor of 100 percent

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since the nonstop portion of the operations can be as long as one hour. These standards allow NJ TRANSIT to optimize the amount of energy expended to accommodate a passenger mile.

Like many smaller systems, though, we must schedule a number of routes based on policy and not demand. In this instance the number of passenger miles per vehicle mile drops significantly and the amount of energy required to accommodate a passenger mile increases. From an operating point of view, there is very little that can be done to overcome this situation. The ability to sell these unused seats is largely a function of the agressiveness of the Agency's Marketing Department.

3. Decrease the Number of Nonproductive Miles - Any transit system generates nonproductive miles in order to position equipment on various lines prior to morning or afternoon rush hour periods. The same miles are generally required to return the vehicle to its operating base. A decrease in the total amount of these miles will decrease total fuel consumption and the amount of energy required to accommodate a passenger mile. NJ TRANSIT presently stores a signficant number of buses near the Port Authority Bus Terminal between the rush hour periods. If these buses were returned to their base, we would incur approximately ___ annual vehicle miles which is ___ percent of our total mileage. Additionally, we would consume ___ gallons of diesel fuel to support this mileage.

The effectiveness of improved operating strategies to improve fuel efficiency is very system specific. It is an area which must be investigated first as part of an overall program to decrease total energy consumption.

Improved Diesel Technology

A complete session is being devoted to this topic so I will discuss it very briefly. The industry is now recovering from the snydrome that bigger is better. In the late sixties, the V-8 engine became very popular. It improved street performance by improving acceleration and the ability to perform on grades. Unfortunately, it also increased fuel consumption. This was not an important factor at the time and did not become one until the energy crisis of the mid-1970's. At the present time, the standard engine is the turbo charged V-6 engine. This engine provides comparable operating performance but improves upon fuel consumption. Turbo charger technology has been available for some time but has only recently been applied to buses. Improvements are still necessary in improving overall diesel engine efficiency if it is to remain cost effective in future years. Some of these improvements include:

- Better optimization of the fuel combustion process;
- Improved environmental controls;
- Optimization of power output for unit of energy input.

The overall efficiency of the diesel may be improved by coupling it with some form of stored energy system. Such a system could possibly smooth out the cyclical power cycle of the diesel and reduce energy consumption. All of these improvements must be made without negatively impacting the engines overall performance and its proven reliability.

Electrification

The availability of electric propulsion presents the transit operator with the greatest number of options for ecycling or reducing the amount of energy consumed per passenger mile. The application of state-of-the-art technology can lead to significant power savings. Systems currently employing electric traction can easily avail themselves of this technology by incorporating it in ongoing equipment purchases. The agency which has no electric propulsion or a very marginal amount is faced with some rather complex procurement decisions. In order to obtain the benefits associated with electric traction, an infrastructure must be put in place. Significant capital outlays must be made regardless of the mode employed: heavy rail, light rail or trolley coach. Typically, the unit of energy required to provide a passenger mile decreases with the use of trolley coaches and even more so with light and heavy rail systems. This statement is dependent upon achieving optimum utilization of each mode's design capacity.

An electrified transit system automatically enjoys certain advantages over a diesel power system. The electrified system draws energy only when it is required whereas a diesel requires energy even when it is idling. The diesel engine must also be designed to provide the maximum amount of power it will be called upon to deliver. The electrical power system is designed to provide only a fraction of the total power required by all units. This, of course, relates to the fact that, while some vehicles are accelerating, others are braking; while some are motoring, others are idling.

State-of-the-art technology is making even further improvements in the area of energy reduction. The following are a few examples:

- Propulsion Systems - Propulsion control systems of the past employed step resistor systems. Once the vehicle started moving, the power was dissipated in resistors until full voltage could be placed across the motor(s). Chopper systems which were first employed in Europe have now become common place in this country. This system "turns on" power only when it is required. Chopper systems have generated power savings in the range of 11 to 18 percent depending upon the specific application. Those systems whose characteristics include a significant amount of stop and go operation and/or have relatively low on board utility loads should experience higher savings. Pulse width modulations systems, which employ AC motor as opposed to the standard DC motors, also provide energy savings. The magnitude of these savings is not as well documented since there are fewer applications of these systems.

- Regeneration - Regeneration can raise the level of savings to well above 20 percent for many systems. The key to the amount of savings is tied to the overall receptivity of the electrical system. Receptivity is the system's ability to absorb power generated through normal service braking or when descending grades. It is theorized that PWM systems can generate a power savings of 24 percent if the electrical system is receptive 50 percent of the time. The savings for a chopper system are probably the same or somewhat higher. It should be pointed out that regeneration is not a new method but has been available for a number of years. The Milwaukee Road demonstrated the benefits regeneration can provide when, in the 1930's, it scheduled trains to ascend and descend the Rocky Mountains so that the latter could supply power to the former.

- Power Conversion and Distribution Systems - Solid state conversion systems have reduced power losses associated with the power conversion equipment. Additional power savings can be achieved in trolley coach operations by employing a feederless distribution system. Such systems use closely spaced substations of 500 to 1,000 KW of capacity. The distance between substation and coach is reduced as is the associated line power loss.

The electrification of transit services, as indicated above, can be a very capital intensive undertaking. Consider the costs associated with the conversion to trolley coaches which include:

Item	Cost
- Overhead & poles	$400,000/mile
- Substations/500 KW	$150,000/station
- Vehicles	$200,000/vehicle

Offsetting these costs, trolley coaches are less expensive to service, maintain and operate. Additionally, they have a life that is more than double that of the diesel bus. The costs associated with light and heavy rail installations are more excessive. Unlike the trolley coach, both of these modes offer significant increases in production since they can handle far greater numbers of passenger miles/revenue miles.

The decision to electrify depends on more than a decision to conserve energy. All the associated cost factors must be brought together in a life cycle cost study that will determine the appropriate course of action. If electrification is to be endorsed, particularly trolley coaches, it must reduce operating costs associated with existing operations. Practically every system in the country is faced with pressures to lower or at least hold constant its operating budget. It is interesting to note that in a present worth analysis which compared trolley coaches and diesel buses in Vancouver, the deciding factor for the former were the cost and consumption differences between diesel oil and electricity.

Electrification must also compete with other uses for capital dollars that are not available in unlimited supply. This is especially true in major urban areas which support large bus fleets and in many cases a sizable rail network. Many systems are coping with the problems associated with years of deferred maintenance or are in a position of having to replace existing facilities whose useful life is at an end.

New Technology

Technology will be required to identify new avenues where energy savings can be made. Many of these new approaches are being discussed at this conference while other are not yet off the drawing board. A preponderance of the new ideas deal with stored energy systems. These systems include:

- Flywheel Systems - Extensive research has been conducted in this area but when one views the results to date, the conclusions are not overwhelming. The system has a significant weight disadvantage coupled with a need to be recharged frequently. At the present time, this technology is a long way from main line applications.

- Hydraulic Accumulators - This method appears to be in its infancy as it relates to applications in the transit field. It may, if successful, build on the old diesel-electric drive systems which have not been used the transit industry in some years.

- Batteries - Technology has been improving the number of ampere hours that can be delivered per unit of batter weight. Unfortunately, the cost effectiveness of battery has not improved to the point where it is suitable for main line applications.

When new technology is considered, it must be remembered that one of the primary responsibilities of any mass transit agency is to provide its rider with quality transportation services. This translates into reliable on-time service with as few missed trips as possible. All new technology will first be viewed in light of its impact on the provision of quality transportation services. The primary thrust of the new technology, be it energy savings or otherwise, becomes a secondary importance.

The experience with new technology has not been one of the brighter spots in the recent history of the transit industry. Many of the major rail equipment procurements have been deeply mired in problems affecting unit availability and its reliable operation. This situation in our industry has lead many operators to seek proven off-the-shelf rather than state-of-the-art equipment. Some examples are the recent LRV orders in San Diego and Calgary. Even the new bus designs have provided theiroperators with untold problems which had the effect of downgrading the quality of service. These unfortunate experiences have made the industry largely technology "shy". In order to protect service quality, transit agencies are willing to purchase yesterday's technology.

Conclusion

Let me conclude very quickly on my perspective as a transit operator as it relates to the subject of this presentation:

1. Energy conservation starts at home. Transit operators mostly look at the present operating strategies to ascertain where savings can be realized.

2. Further steps must be taken to improve the efficiency of the diesel engine. Standing alone it is questionable as to what degree this efficiency can be improved. Coupled with a stored energy system its efficiency may be further improved.

3. Electrification can reduce power requirements. Existing systems can take advantage of reliable new technology which provides additional savings. New systems must closely consider life cycle cost implication to ascertain if factors other than energy will collectively produce a positive conclusion. Capital dollars must also be available and free from other encumbrances to allow such a project to move forward.

4. New technology which is proven to reduce energy consumption must also be able to show that will not negatively impact "quality" transportation services.

VTS — THE TRACTION SYSTEM THAT TURNS ENERGY LOSSES INTO RECYCLE POWER

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SUMMARY

In vehicles such as city buses, trams and underground trains, the ability to store brake energy and Recycle it to the wheels for use when accelerating is of great advantage.

Volvo Flygmotor has developed systems for storing energy and transmitting power in vehicles. The Vehicle Traction System – VTS. The VTS in a single sweep solves several of the problems that conventional transmission systems have. With the VTS you can utilize Recycle Power, the energy that until now has been lost every time the brakes are applied.

The VTS is a Continuously Variable hydrostatic Transmission, which may be used purely as a main drive CVT for vehicles and which may be combined with different types of energy storage systems.

The VTS with energy storage in a flywheel and a six liter diesel engine can for instance replace the gearbox and the standard ten liter engine of a 16 ton city bus. With the VTS the engine does not have to be made for peak power requirements. The stored energy takes care of peak loads.

The VTS with energy storage in hydraulic accumulators may be used in addition to the standard drive train in order to save fuel and the environment and to minimize maintenance costs for the gearbox and the engine.

The hydrostatic transmission has many desirable features. It is adaptable to all kinds of vehicles with various installation requirements and it offers excellent controllability when combined with modern electronics. We have focused on developing the VTS for buses, railway vehicles and industrial tractors.

INTRODUCTION

Volvo Flygmotor AB, located in the south west of Sweden, is a wholly-owned subsidiary of the Volvo Group of companies. Volvo is the largest industrial group in the Nordic area.

Volvo Flygmotor was founded in 1930. Today the company employs 3,000 people and has a turnover of approximately SEK 1,000 M. Until 10 years ago production was concentrated on aircraft engines for the Swedish Air Force, and this is a major part of our work today too. In the long run the company has to expect a reduction in the military work load, which requires new strategy. Great efforts have been made to find new products. Naturally, these efforts have been focused on products requiring advanced development and manufacturing capabilities.

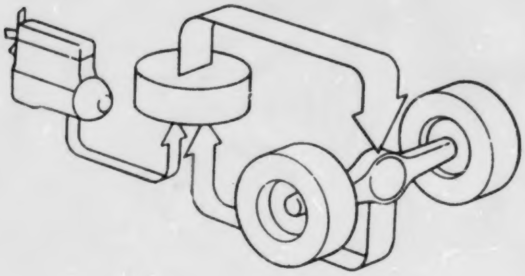
Thus the company formed separate divisions during the 70's for hydraulics, heaters and diesel engine parts. The hydraulic division has grown rapidly and is a subsidiary of Volvo Flygmotor today with a wide range of hydraulic pumps and motors on its program, of which the bent axis units are well-known all over the world for their high efficiency.

Having in house experience in hydraulics and advanced electronic controls, Volvo Flygmotor decided to look into the transmission sector. This resulted in the development of the VTS, a power package of hydraulics and electronics. VTS is also the name of the new division of Volvo Flygmotor which handles these transmission systems.

The VTS as described in detail below offers the following alternatives:

- pure hydrostatic drive, computerized and continuously variable transmission. It gives the vehicle a very high degree of comfort with smooth and jerkfree acceleration and deceleration. It also has built in automatic slip and skid control of the wheels.
- hydrostatic transmission with energy storage in a flywheel, rotating at up to 10,000 r.p.m. This is also a continuously variable transmission with the advantages mentioned above. Thanks to Recycle Power it also improves fuel economy by 20 – 30 % and generates proportionally less exhaust emissions. A fully charged flywheel has

an energy content of 2.3 kWh, which for instance makes it possible to drive a 16 ton city bus 1,200 meters completely exhaust free with the diesel engine shut off.



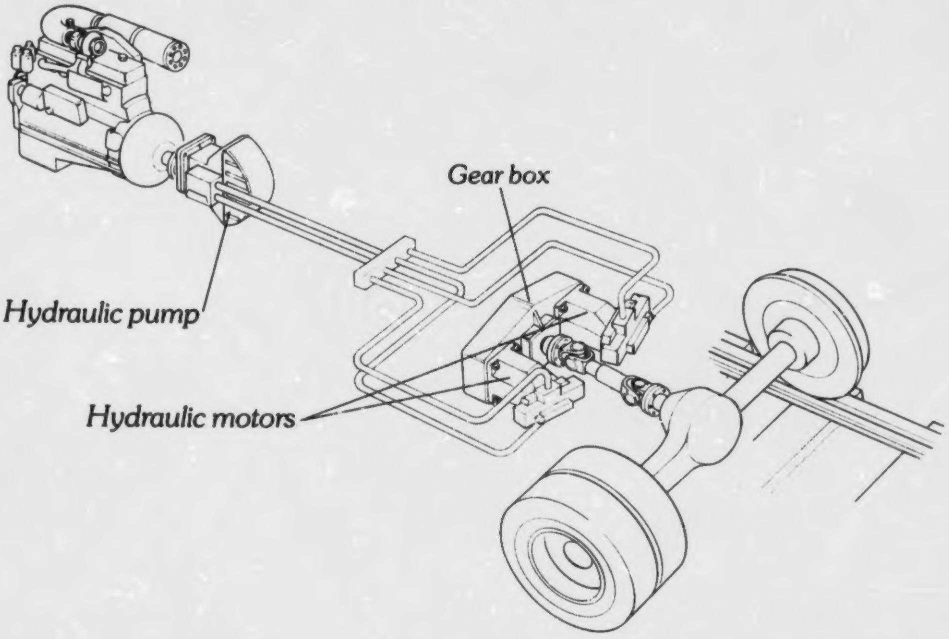
- split torque transmission with energy storage in hydraulic accumulators. In this case retardation and the first phase of acceleration are hydrostatic and normal drive is mechanical. Thanks to Recycle Power this system improves fuel economy by 30 – 50 % and reduces emissions. The main drive (gearbox and engine) is used proportionally less, which decreases maintenance costs.

Basic hydrostatic system

WORKING PRINCIPLE

A pump and one or more motors are connected by flexible hoses. The pump, which is driven by any type of prime mover, produces a flow under high pressure. Passing the hydraulic motor, the thus energized flow forces the motor shaft to rotate and drives the vehicle in turn. Having passed the hydraulic motor, the fluid is pumped back to the pump inlet, pressurized to drive the motor and so on.

This basically simple way of transmitting mechanical power provides numerous advantages in comparison with other types of transmissions. Evidence of this will be shown by describing the working principle in more detail.



NO CLUTCH

The pump can be built to produce a variable flow without changing the speed of the pump shaft. Specifically zero flow may be attained, which allows the transmission to work without a mechanical clutch.

FREE ENGINE SPEED

When the pump is set to produce zero flow, the prime mover may be run at any speed. To set the vehicle in motion and accelerate, the pump is controlled to continuously increase the flow. Most other transmissions start accelerating by increasing the speed of the prime mover, which is a disadvantage when optimizing running conditions. The constant speed capability of the prime mover is of particular interest for electrically driven vehicles. This will be described further on.

NO GEARBOX

A variable pump can produce pressurized fluid in both directions. This fact tells us that forward and reverse drives are inherent in the transmission and eliminates the need of a gearbox. Speed and acceleration are equally good in both directions. This of course is of little interest for buses but is a must for motor coaches, subways, trams and other rail vehicles.

"WEARFREE" HYDROSTATIC BRAKING

The pump and motor have basically the same construction which offers the potential of transmitting power in both directions. This means that the vehicle can feed brake power back into the prime mover in the same way a simple cardan shaft would.

Brake energy, thus fed through the transmission, may be stored or dissipated in a number of ways;

- A restriction valve in the hydraulic circuit turns brake energy into heat in the fluid which in turn may be dissipated in a fluid/air cooler.
- A hydrodynamic retarder, mounted on the pump shaft dissipates energy in the same way as when it is connected to the cardan shaft of a bus. However, utilizing the possibilities of running the pump at constant speed, the retarder may run at this same speed and gives full brake effect all the way down to a full stop. This is an important advantage in comparison with retarders working on cardan shafts or hydrodynamic transmissions.
- Exhaust braking in diesel engine applications can be very effective when running the engine at a high and constant speed which again is an inherent possibility of the hydrostatic transmission.
- Hydraulic accumulators may be utilized.
- A high speed flywheel may be utilized.

Common to all four braking principles described here, is the fact that they are fully effective over the entire speed range, there is no mechanical wear, and no disc or drum brakes are involved.

SIMPLE SLIP AND SKID CONTROL

Wheel slip during acceleration and the opposite problem, wheel skid due to overbraking, are of great importance for rail vehicles but also create problems for road vehicles.

Today, these two problems have been solved separately – an antislip device working to control the power of the prime mover or the gearbox, and an antiskid device to control the application of the friction brake system. In a hydrostatic transmission with any type of brake system (restriction valve, retarder, exhaust, accumulator, flywheel) slip and skid are equal phenomena and may be precisely and automatically controlled by altering the pressure of the hydraulic circuit. Control is executed through the servo for pump control. This provides the great advantage of controlling slip and skid without any extra equipment.

VERSATILE INSTALLATION

When designing a vehicle with an electrical, mechanical or hydrodynamic transmission, the versatility of the design is limited. The hydrostatic alternative offers in principal an infinite number of installation configurations, due to the simple fact that flexible hoses connect pumps and motors. For example a bus with the engine mounted in the front, under the floor or across the rear end may be equipped with identical transmissions. Renovations and alterations, not unusual with long lived rail vehicles, are accomplished with the hydrostatic drive train in a cost effective way.

GOOD DURABILITY

Environmental endurance is of utmost importance to all passenger vehicles. In this respect, the bogie of a rail vehicle represents a highly undesirable place for an electric motor. It has to withstand high g forces (> 50 g), temperature variations, rain, snow, dust, mechanical damage etc. Today, technicians have overcome these problems but at a very high cost.

A hydraulic motor, installed in a bogie, easily withstands these tough conditions. Its light weight (1/10 that of an electric motor of the same power) minimizes g force problems and the unsprung mass as well, which improves riding comfort.

Furthermore, the machine is hermetically sealed and operates embedded in snow, ice and even under water if such conditions should arise. Of course, the electric motor and hydraulic pump are necessary but these may be mounted above floor or in any other protected area. Environmental requirements are then heavily reduced and so is the price.

SINGLE ENGINE

Another positive aspect of the hydrostatic transmission is that one electric motor can serve all four axles of a Light Rail Vehicle, for instance a tram or subway.

BASIC SYSTEM ADVANTAGES

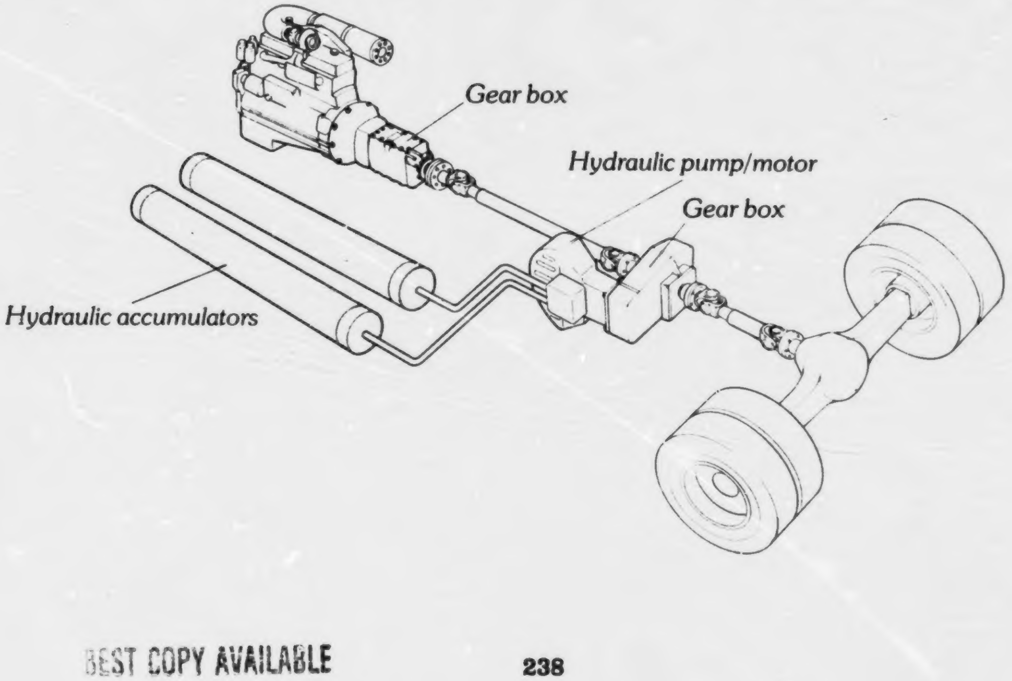
To sum up the description above, a hydrostatic transmission offers the following:

- No clutch needed
- Prime mover runs at any speed
- Forward and reverse without gearbox
- "Wearfree" braking capability
- Simple antislip and antiskid control
- Energy storage in accumulator/flywheel may be added
- Versatile installation
- Good environmental durability
- One electrical motor substitutes four

Hydraulic accumulator for Recycle Power

WORKING PRINCIPLE

The VTS accumulator system is used together with a standard mechanical cardan shaft type of transmission and consists of three mechanical units; a gearbox, a pump and a hydraulic accumulator.



When the vehicle accelerates, pressurized fluid drives the pump (making it a motor) which via a gearbox drives the cardan shaft. Having finished acceleration, the stored energy is consumed and the prime mover (which up to now has been idling) takes over. During the brake sequence the pump is driven by the cardan shaft and feeds pressurized fluid back to the accumulator.

SYSTEM ADVANTAGES

The simplicity of the VTS accumulator system is striking and yet it offers the following advantages:

- Installation may be made in new as well as used vehicles thanks to minor mechanical changes.
- Given a suitable driving cycle, a 30 – 50 % improvement in fuel economy has been noted.
- Reduced exhaust emissions.
- The life times of the prime mover and gearbox are increased considerably as they are inactive during each acceleration and deceleration sequence. Practically no wear of the standard friction brakes.
- The vehicle has operational flexibility for both long distances and city traffic without modifications as the system is disconnected when not efficient (long distance).
- A system failure does not put the vehicle out of service thus ensuring high availability.

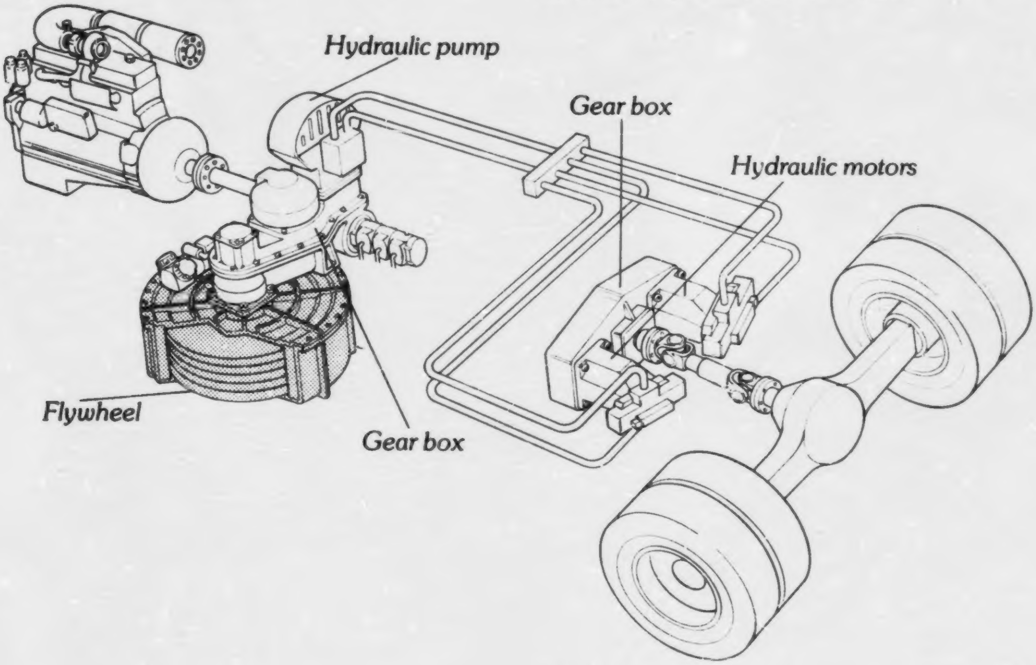
Flywheel for Recycle Power

WORKING PRINCIPLE

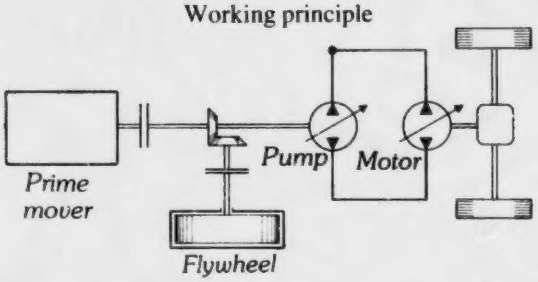
The VTS flywheel concept basically includes a

- 5 disc steel flywheel running at a maximum of 10,000 r.p.m. equivalent to an energy of 2.3 kWh.
- Gearbox for driving the pump.
- Pump, displacement 160 ccm^3/rev.

The pump is mechanically connected to the prime mover and the flywheel. Both connections include clutches which are operated to transmit power from the prime mover, the flywheel, both simultaneously or neither of the two. In doing so, various characteristics of the transmission are utilized.



Working principle



1. Normal operating mode.

   When the prime mover clutch is disengaged and the flywheel clutch is engaged, power may be fed from the flywheel to accelerate the vehicle. While doing this the prime mover is idling or shut off, the latter of course gives the best energy economy.

   By switching the high pressure sides of the transmission, the pump works as a motor and transmits recycle power to the flywheel.

2. Prime mover operating mode

   When both clutches are engaged, the prime mover becomes part of the transmission. The objective of this operating mode is to compensate the flywheel for efficiency losses in the transmission and for vehicle drag. The prime mover is engaged as long as necessary to restore a predetermined level of energy in the vehicle-flywheel kinetic energy system.

3. Shunting mode

   When the prime mover clutch is engaged and the flywheel clutch is disengaged, the transmission functions as the basic transmission described earlier. However, in a typical flywheel application the flywheel is the prime power supply. The shunting mode is used for moving the vehicle in and out of garages etc. when it is not worth waiting the time it takes (2 – 3 min.) to charge the flywheel.

4. Parking mode

   When both clutches are disengaged the transmission is not operational. The pump and the flywheel gearbox do not rotate minimizing mechanical efficiency losses. The parking mode is chosen when there is a few minutes waiting time, for instance, before the next run starts.

SYSTEM ADVANTAGES

- Given a suitable driving cycle, a 20 – 30 % improvement in fuel economy has been shown.
- No exhaust emissions when the prime mover is shut off.
- High energy level. The flywheel stores 2.3 kWh which enables a 16 ton city bus to negotiate 1,200 m with 3 full stops at full performance on stored energy alone. This feature is of interest from the environmental point of view but also for trolley bus operators wishing to improve their passenger service by leaving the electrified lines for stops in residential areas.
- High power output. The performance of a flywheel system is limited by the size of the pump, not by the prime mover. Thus very high power levels may be attained. For example, a system with a 100 kW diesel engine has a maximum rating of 225 kW.

Control logics

Now, a technical part that has not been illuminated, the control system. The rhetorical question is: Won't doing all this make the controls sophisticated beyond sound judgement and acceptable price?

The basic transmission has only one major servo, namely the electrohydraulic servo for the pump unit. By actuating this servo, functions like clutching, forward, reverse, antislip, antiskid, speed and power are performed. To cover a greater speed range, most transmissions include variable hydraulic motors as well and that adds a proportional electrohydraulic servo to the basic controls.

As an example of the control logic we will study a diesel engine with a hydrostatic transmission. Such a system would require the following control signals:

INFORMATION RECEIVED

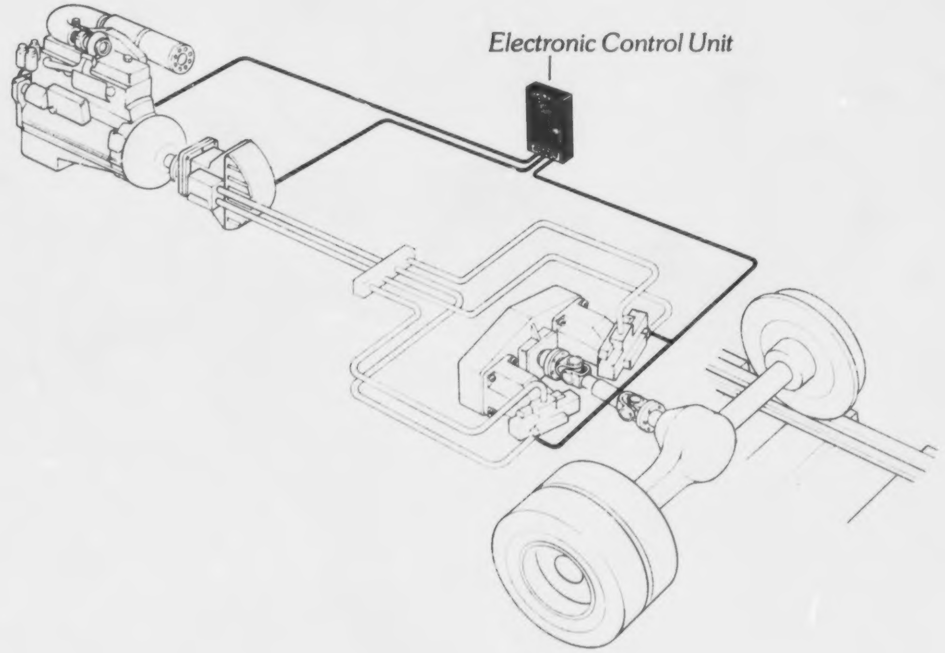
- A potentiometer, operated by the driver, informs the control logics about a request for acceleration, constant speed, braking, parking etc.
- A speed sensor (likely to be a pulse pickup) mounted on the driven axle(s) informs about vehicle speed and deviating values, which show slip and skid conditions.
- A pressure gauge gives the hydraulic fluid pressure. This parameter is vital for smooth and accurate control.
- A speed sensor (pulse pickup) measures the diesel engine speed.
- To improve the accuracy of pressure control, a potentiometer measures the stroke of the hydraulic pump.

GOVERNING SIGNALS

- An electrohydraulic servo valve controls the variable stroke of the pump (at constant pump speed, this is equivalent to a direct flow control).
- A proportional electrohydraulic servo sets the stroke of the hydraulic motor. Integrated mechanical feed-back forms a closed circuit control.
- The power level of the diesel engine is governed by a step motor linked to a gearbox. Alternatively, a linear motor or electrohydraulic cylinder may be used.

ELECTRONIC CONTROL UNIT

The integration of input and output signals as outlined above is of course accomplished with an Electronic Control Unit (ECU). VTS has developed an ECU especially for these transmissions. Apart from the direct controls, the ECU checks itself and can also detect numerous technical malfunctions. The complete unit measures 440 × 250 × 50 mm, weighs 3.5 kg and has an MTBF in excess of 4,000 hours and an estimated lifetime of 70,000 running hours.



Transmission objectives

We have now presented three novel designs of a modern transmission for passenger traffic, all based on the technical features inherent in a hydrostatic transmission. Naturally all three are not equally advantageous to every operator. The following transmission objectives are presented in terms of different operator requirements.

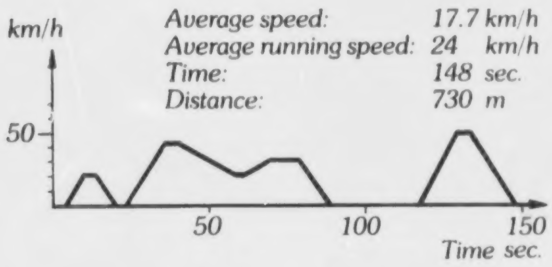
LOW INITIAL COSTS

Today it is generally well-known that the price does not tell the operator much about the real LCC. Fuel consumption and maintenance are two factors which should be judged together.

This makes the VTS basic transmission highly competitive to existing alternatives, especially hydrodynamical and electrical transmissions for rail vehicles.

LOW FUEL COSTS

For a city bus, the VTS accumulator system stands out as a winner over any existing alternative as long as the traffic pattern is suitable with rather intense start and stop cycling. Following the illustrated cycle, when comparing the VTS to a modern powershift gearbox including lockup. 50 % extra milage is obtained, from every gallon.



LOW TOTAL EXHAUST EMISSION

When burning less fuel the total exhaust emission decreases proportionally.

NO EMISSION IN SENSITIVE AREAS

Some operators may have routes passing tunnels, hospital zones, parks, indoor stations etc. demanding exhaust free operation. The only existing solutions are batteries or trolley lines. With the VTS flywheel a low cost diesel powered vehicle may be considered.

CONSTANT SPEED ELECTRIC MOTOR

This objective has been impossible until now. The very simple electrical motor design that the system permits has never been considered. This means a motor can reach its running speed without any load on its shaft. This further reduces weight and complex controls to a minimum. The VTS transmission enables a constant speed capability for the electric motor.

REDUCED SUBWAY INVESTMENT

A subway operator may reduce the investment in power supply. The installation may be limited to parts of the line and the flywheel takes the coaches across the dead zones.

ADDITIONAL POWER

The flywheel or the accumulator may be used together with the prime mover and thus multiply transmission power. A fundamental difference between the flywheel and the accumulator is that the former stores 5 times more energy making it the best choice for the operator who wants extra power.

For bus routes, an operator may choose a less powerful engine and let the VTS system cover peak loads.

"WEARFREE" BRAKING

The cost and maintenance of mechanical brake systems varies for different vehicles. However, all mechanical brakes represent some additional costs, which may be eliminated by any VTS transmission.

FULL CVT

Many major public transport companies face the problems of handling more sophisticated transmissions with less skilled personnel. This has led to the development of automatic power shift gearboxes. The resulting reduction in efficiency has made it necessary to add mechanical lockup systems. However, an absolutely jerkfree and high efficiency transmission is not attainable using existing technology.

When in operation a VTS transmission is a full CVT covering the entire speed range. Actually the efficiency of a hydrostatic transmission is somewhat less than, for instance, that of a purely mechanical gearbox. But with optimized diesel operation and the Recycle Power capability the VTS transmission has demonstrated undisputable proof of fuel economy.

INSTALLATION VERSATILITY

An operator contemplating a new coach design for his forth-coming fleet or renovation of his existing one, frequently finds that the prime mover and transmission are contrary to his wishes.

A hydrostatic transmission makes it possible to mount the prime mover practically anywhere in the vehicle. The accumulator system, however, does not provide this possibility for the diesel engine although the accumulator itself may be mounted wherever suitable.

Customers requirement	Basic Hydrostatic System	Hydraulic Accumulator System	Flywheel System
Low initial cost	X	X	
Driving long distance without prime mover			X
Low fuel costs		X	X
Constant speed prime mover	X		
Additional power		X	X
"Wearfree" braking	X	X	X
Full CVT capabilities	X		X
Installation versatility	X	X	X
Low maintenance costs		X	

Status of VTS development

The development of VTS has been going on since 1979, and has passed through a number of stages, including computer simulations, rig tests and tests with experimental vehicles.

During 1982 and -83 a number of prototypes have been made and put into regular service in order to gain field test results. Thus we have today city buses, rail buses, shunting engines and fork lift tractors running in field tests. These field tests are being performed in Sweden and will soon be carried out in major European cities as well.

Experiences from the field tests will form the basis for the final design of the VTS transmissions for production in series in 1985-86.

HYDRAULIC ACCUMULATOR TECHNOLOGY BOOSTS TRANSIT BUS FUEL ECONOMY

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SUMMARY

An investigation into the use of current hydraulic accumulator technology to regenerate braking energy in urban transit buses indicates that this system can improve vehicle fuel economy by approximately 50 percent. This savings plus that achieved through extended brake life can mean nearly $70,000 saved per vehicle over a 12-year lifetime.

The objective of this investigation was to determine the feasibility of using Stored Hydraulic Energy Propulsion (SHEP) technology in current transit coaches, and to present an evaluation of the fuel savings and economic cost/benefit of the SHEP systems which are currently in the concept and hardware stages of development for transit coaches. This paper summarizes the findings of the study, which was funded by the U.S. Department of Transportation, Urban Mass Transportation Administration. The study report, "An Investigation of the Applicability of a Stored Hydraulic Energy Propulsion System to a Conventional Bus"(1),* was the product of work performed for the Tri-County Metropolitan Transportation District of Portland, Oregon.

The analysis included a determination of the current status of SHEP systems proposed or developed anywhere in the world. The costs and benefits resulting from the operation of the proposed systems were then analyzed from actual and computer-projected data.

Two prototype systems, specifically applied to transit coaches, were found to be currently under development in Europe: "Hydrobus II" developed by the M.A.N. Corporation of Germany and "Hybrid Bus" developed by the Technical University of Denmark (T.U of D.). Two other systems were found to be applicable to transit coaches. These were the Inertial Storage Transmission System developed by Advanced Energy Systems (AES) of Portland, Oregon (division of L. B. Nelson Corporation), and the "A-Bus" concept (not yet developed into hardware) by Energy Research and Generation, Inc. (ERG) of Oakland, California.

This paper will discuss the benefits of these four systems in general and the simple, add-on type of retarder/regenerator system developed by the Technical University of Denmark in particular. The T.U. of D. system is believed to have wide adaptability to both the retrofit market and the new bus market.

The fuel saved was calculated for each system that was proposed or already in the development stage. The miles-per-gallon figures were estimated by computer simulation for a range of system efficiencies. The system costs were estimated through interviews with hydraulic hardware distributors, experts in the field, and the system developers themselves. Whereas component costs were readily available, judgment was required to estimate the probable production cost and cost of sales for these systems. The overall benefit of these systems is expressed in total dollars saved over the lifetime of the coach after the system has paid back its original investment cost.

ENERGY MANAGEMENT IN TRANSIT BUSES

The propulsion systems in transit coaches are generally diesel engines that convert diesel fuel into mechanical energy. This energy is applied to the road surface to accelerate the vehicle and maintain its speed against the resistive forces of air friction and tire rolling resistance.

In conventional transit coach designs, the energy of the moving coach can be dissipated in one of two ways:

- The driver can take his foot off the accelerator pedal, and the resistive forces can slow the vehicle down to the desired speed.
- The driver can apply an additional resistive force--the brakes.

In either case the kinetic energy of the moving coach is dissipated into a nonrecoverable form.

The purpose of all regenerative braking schemes is to productively reclaim the otherwise wasted energy and reuse it to accelerate the vehicle. Acceleration demands the greatest energy expenditure, and good energy management entails reducing this energy requirement if fuel is to be conserved.

The amount of energy that can be reclaimed is most dependent on the duty cycle of the vehicle. A duty cycle is an often-repeated mode of operation for a given class of vehicles. For example, line-haul trucks are generally accelerated up to cruising speed on a highway and then required to maintain that same speed as traffic permits for hours on end. An energy management study of line-haul trucks would point toward saving energy and fuel by reducing aerodynamic and rolling friction resistances. Since such a small percentage of their operation is spent stopping, it is easy to see that costly and complicated gadgets to save braking energy would produce a small percentage improvement in fuel savings. The converse is true for transit coaches.

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* Numbers in parentheses designate references at end of paper.

The advanced design bus (ADB) cycle shown in Figure 1 was the representative duty cycle used to analyze the energy expended by a transit coach. The ADB duty cycle is the transit industry standard for bus fuel economy testing. This cycle is the design criterion for advanced design buses.

The cycle consists of four distinct driving modes: central business district (CBD), arterial, idle, and commuter. It is important to note that bus performance determines the acceleration rate experienced during the cycle. This is a significant difference from other test cycles which specify a fixed driving speed and constant acceleration rates.

Although no one cycle can exactly simulate every transit property's operations, the central business district portion of the ADB cycle is considered to provide a good basis for comparison of the regenerative systems.

The energy and the corresponding fuel saved by each system over the ADB cycle were calculated by applying various system efficiency factors for each proposed system. Figure 2 is a sample plot that shows the effect of overall system efficiency on fuel economy for a coach at fully seated capacity. A computer can help analyze the effects of coach weight, duty cycle variations, and other factors on system performance. The use of a computer directs the engineering of an effective regenerative system, and permits an analysis of the various hardware schemes.

TECHNICAL EVALUATION OF THE SYSTEMS

The four systems mentioned earlier can be grouped in two functional categories:

- Buffered operation
- Parallel operation.

Buffered Operation

The current operating profile of the AES system and the proposed operating profile of the ERG system are examples of buffered energy systems. The diesel engine operates at its optimum fuel consumption speed and torque to maintain the energy level in the hydraulic accumulator system. The engine is generally turned off during the acceleration and deceleration of the vehicle, and is used only for supplying power during sustained cruising. The hydraulic motor powers the wheels of the

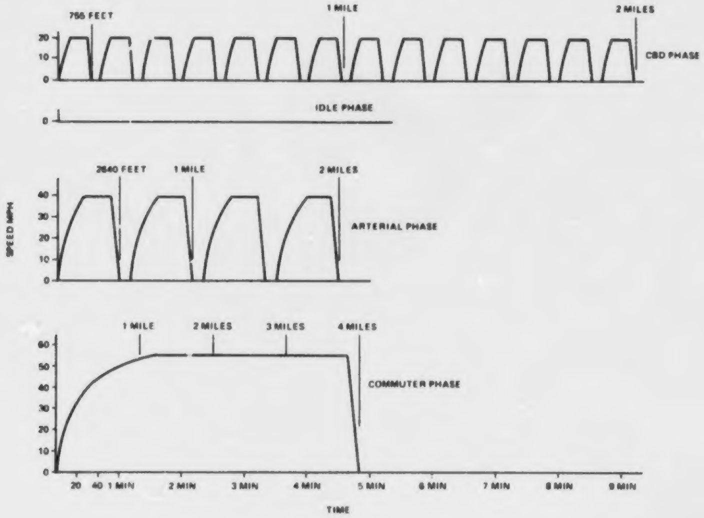

Figure 1. ADB Operating Duty Cycle

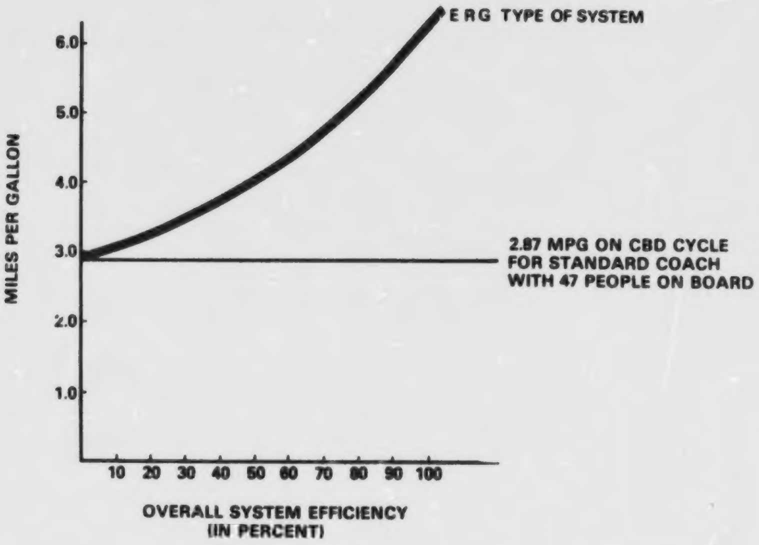

Figure 2. Fuel Economy Versus System Efficiency (Sample Plot)

coach most of the time. The diesel engine can put power directly to the wheels of the vehicle in some systems at speeds above 35 mph. In these systems, the peak energy requirement for acceleration is supplied by stored energy. This buffers the demand placed on the diesel engine.

Parallel Operation

The M.A.N. and T.U. of D. systems use the energy from the storage tanks to accelerate the vehicle and then switch to diesel engine power as required to complete the acceleration and for cruising. It is possible to use both the diesel engine and the hydraulic motor simultaneously if desired since both power sources have parallel power paths to the rear wheels. The power path in the M.A.N. system is integrated into a single transmission unit, whereas the T.U. of D. unit is an add-on, power-pack type of installation. In both cases the engine idles while it is not in use. This alleviates the problems of powering accessories and engine restart after the engine has been shut off. Engine durability may also be improved by reducing the number of restarts and maintaining more constant operating temperatures. Some of the overall energy savings improvement is lost by idling the engine and not buffering the energy demands placed on it.

The relative fuel economy potential of each type of system is shown graphically in Figure 3. The buffered operating systems can achieve consistently higher fuel economy improvements over the parallel operating systems.

The most likely fuel economy improvements possible with each type of system are 52 to 78 percent for the buffered system and 39 to 62 percent for the parallel system. Both estimations are based on the CBD portion of the ADB duty cycle. T.U. of D. has achieved a 70 percent overall system operating efficiency in passenger service, that is, fuel economy improvement of approximately 50 percent (33 percent fuel consumption reduction).

With the Booz, Allen & Hamilton computer simulation, it was possible to estimate the effects of variations to the standard CBD cycle on fuel economy improvements. With the T.U. of D. system as a base, the effects of altitude, cycle maximum speed, number of stops per mile, deceleration rate, and accessory load changes were calculated. The fuel economy changes are shown in Table 1.

It can be seen that increasing the number of stops per mile and increasing the rate of deceleration improve the fuel economy savings potential of these systems. Likewise, high-altitude operation, higher average speeds, slower deceleration rates, and increased accessory loads reduce the effectiveness of regenerative braking systems. Under typical operating conditions, hydraulic stored-energy, add-on systems can achieve fuel economy improvements between 38 and 65 percent.

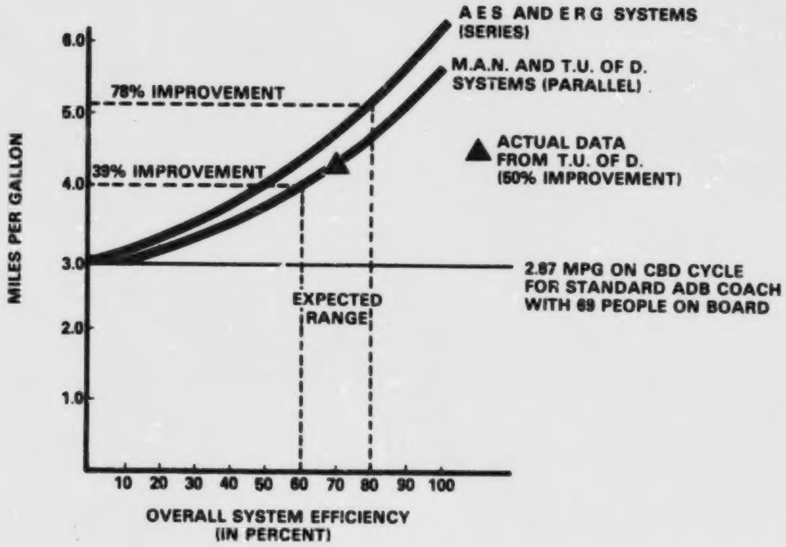

Figure 3. Fuel Economy Versus System Efficiency

Cycle	Variation	Fuel Economy Improvement (%)	Remarks
CBD	--	50	Base case
ART	Max speed 40 mph	38	Higher speed cycle; less stops per mile
CBD	11 stops per mile	65	1.5 time as many stops per mile
ART	6 stops per mile	42	Higher speed and 1.5 more stops than standard ART cycle
CBD	5,280 foot altitude	43	Denver, Colorado operation
CBD	3 ft./sec^2 deceleration	43	Slower deceleration
CBD	5 ft./sec^2 deceleration	49	Slightly slower deceleration
CBD	8 ft./sec^2 deceleration	51	Slightly higher deceleration
CBD	9 ft./sec^2 deceleration	52	Higher deceleration
CBD	Air conditioning load	43	High accessory loads
CBD	System weight equal to 5.8 percent of total vehicle weight	50	Base case--2,000 lb. system weight and 34,000 lbs. coach gross loaded weight
CBD	System weight equal to 7.7 percent of total vehicle weight	40	Lightweight coach--2,000 lb. system weight and coach curb weight of 26,000 lb.

Table 1. Fuel Economy Changes

ECONOMIC EVALUATION OF THE SYSTEMS

The total sale price of a hydraulic regenerative system is made up of many system-specific costs. Costs are particular to the type and quantity of components being used and difficulty of manufacture. The overall system costs and benefits are broken down and estimated in three categories for each system:

- Component (hardware) costs
- Production and sales costs
- Cost recovery (payback period).

Component Costs

Only the M.A.N. and T.U. of D. systems are currently functioning in transit coaches. The AES system is designed for a van, and it is not known what type of hardware will be required for an AES coach system. The ERG system is a paper concept design. Cost estimates (1981 dollars) are shown in Table 2.

To determine the cost/benefit of these systems, an estimated range of component costs was gathered from interviews with industry representatives, experts in the field, and local hydraulic equipment distributors. The estimate, shown in Table 3, should cover the entire range of designs expected for transit coach applications.

Table 2. Manufacturer Estimates of System Cost (Units of 10 or More)

System/Component	T.U. OF D.	M.A.N.	ERG
Motor/Pumps	$ 3,500	$ 3,600	$ 8,000
Accumulator System	4,400	7,000	4,000
Computer Control Box	1,500*	1,000	2,000
Lines and Fittings	500	500*	1,500
Special Parts	1,500	3,750	500*
	$11,500	$15,850	$16,000

* Booz, Allen & Hamilton estimate.

Table 3. Estimated Range of Component Costs (Units of 10 or More)

Component	Cost
Motors/pumps	$2,000- 8,000
Accumulator system	4,000- 8,000
Computer control box	500- 2,000
Lines and fittings	500- 2,000
Special parts	500- 3,000
	$7,500-23,000

Production and Sales Costs

The final sales price of a system is very difficult to estimate even if the system is fully engineered. Each company has its own return on investment and profit goals and requires different mark-ups over the fixed and variable costs of each component. Engineering and computer programming costs will vary with each design, as will manufacturing cost. For example, the M.A.N. system will take nearly 6 years to engineer but at the end of that period will be fully integrated into existing coaches in their own fleet.

The engineering, manufacturing, installation, and sales costs of a system are estimated to be in the range of $5,000 to $20,000 per vehicle when procured in quantities of 10 or more. It is likely that a T.U. of D. unit could cost about $12,000 in component costs and another $10,000 in production and sales costs. This results in a unit expected to sell for $22,000 per bus, with a possible range of about $17,000 to $30,000.

Cost Recovery (Payback Period)

Rather than make guesses at future inflation rates or price increases for diesel fuel, the payback period is based on cost estimates made in 1981 dollars. Estimates of sharply rising diesel fuel prices or inflation rates could make these systems more attractive than they are presently. As a result, the payback periods are based on 1981 prices for equipment and 1981 diesel fuel prices.

The payback time period is calculated as follows:

$$\text{Payback Period} = \frac{A}{B + C - D}$$

where A = system purchase price
B = yearly brake savings
C = yearly fuel savings
D = yearly added maintenance and operating costs.

For systems similar to the simple add-on T.U. of D. prototype:

$$\frac{\$22,000}{\$2500 + \$7000 - \$1500} = 2.75 \text{ year payback period}$$

This payback period can be used as a gauge to determine system utility and commercialization potential. The three factors in the payback equation are:

- Yearly savings (brake and fuel)
- Yearly costs
- System purchase price.

Each is discussed separately below.

BE

Yearly Savings -- These systems will primarily save money by reducing fuel consumption. They will also dramatically reduce the number of brake relinings required per year. Estimates range from $1,500 to $3,000 per year for savings on brake relinings (two to three complete overhauls saved per wheel per year). Figure 4 is a graphical presentation of the fuel savings potential of the four systems. The expected savings of $7,000 is a conservative estimate based on actual T.U. of D. system efficiency and fuel economy potential. The yearly vehicle miles traveled are representative of a new coach during the first 4 to 5 years of service.

Yearly Costs -- M.A.N. has the most operational experience with these systems; however, they were not able to estimate system reliability at this point. Manufacturer reliability data point toward a replacement of one unit out of ten every 2 years. Such a replacement rate would cost the transit property about $500 to $2,000 per year in parts and labor costs. Periodic inspections may be required in addition to those already performed on standard coaches. These inspections could add between $100 and $500 per year in maintenance costs. In addition to the major components, minor components can be expected to fail, adding between $100 and $1,000 in parts and labor to the maintenance costs. The worst case for yearly extra costs equals $3,500, and in the best case, additional maintenance may only be $700. The most likely extra cost is $1,500. The most likely overall yearly savings is $1,000 ($2,500 saved on brakes minus $1,500 additional maintenance).

System Purchase Price -- Figure 5 shows the expected payback (number of years required to recover the initial cost) of the T.U. of D. system, based on the expected ranges of purchase price and operational cost savings. The AES and ERG systems are able to exhibit lower payback periods because of their higher potential for system fuel economy savings.

SUMMARY

The best estimate of payback period for the T.U. of D. type of regenerative braking system is 2.75 years. In other words, after the SHEP system is paid for ($22,000), it will save an additional $47,500 in fuel costs at $1.10 per gallon of diesel fuel over the life of the coach.

In addition, the system will save another $6,000 in brake relinings. The total operating cost saved over the 12-year life of the coach is $69,500 in 1981 dollars ($47,500 after payback).

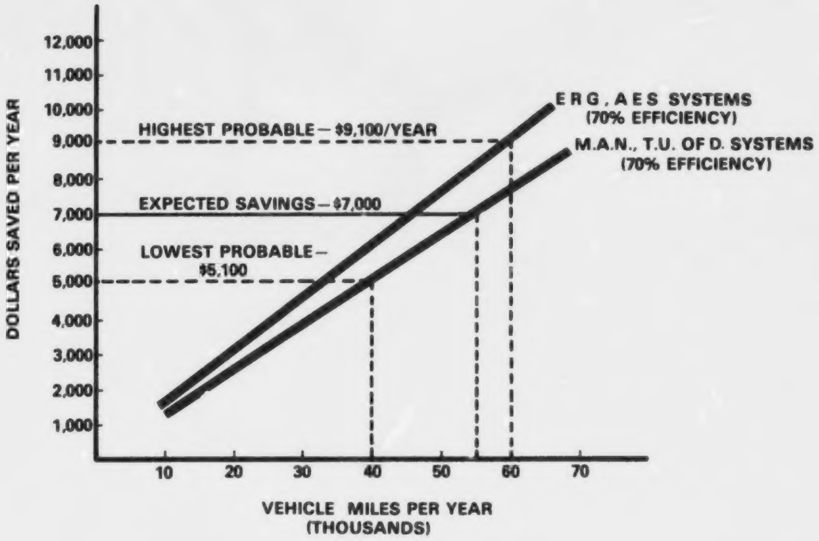

Figure 4. Fuel Savings Potential of the Four Systems

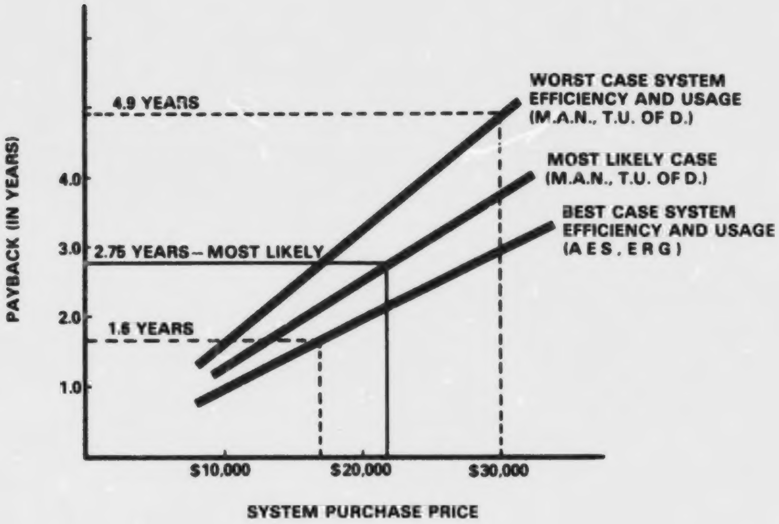

Figure 5. System Price Versus Payback Period

REFERENCES

(1) Booz, Allen & Hamilton Inc. "Transit Bus Fuel Economy Test." U.S. Department of Transportation Report No. BP 80-004, April 1981, NTIS.

(2) Booz, Allen & Hamilton Inc. "Investigation of the Applicability of a Stored Hydraulic Energy Propulsion System to a Conventional Bus." Tri-County Metropolitan Transportation District of Oregon, August 1981.

TRANSIT ENERGY SAVINGS THROUGH REGENERATION

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BACKGROUND

The energy saving potential of regenerative braking has been an important area of focus for transportation engineers for over twenty years since the mass rail transit industry began moving from traditional electro-mechanical cam- controlled propulsion systems to solid state chopper-controlled systems. Experience at the Sao Paulo Metro Rapid Transit System in Brazil using chopper-controlled propulsion with regenerative braking has provided conclusive operating data which show the dramatic impact on energy conservation provided by regeneration.

This paper presents the results of an analysis covering in-service regeneration performance of the Sao Paulo Metro since January , 1977. The Metro began revenue service in 1974 on its North/South Line which is the first of five lines to be built (Figure 1). The North/South Line consists of 17 kilometers of double rail track, 20 passenger stations, and a large yard located at the end of the line.

This line has operated fully automatically since 1975 using 198 cars in six-car trains at speeds up to 100 kilometers per hour. The average operating speed is 34 kilometers per hour. An additional 108 cars using Westinghouse regenerative chopper propulsion were ordered for the North/South Line in 1977. These cars were placed in service beginning in 1979.

Finally, in 1977, another 132 cars equipped with Westinghouse design propulsion were ordered by the Metro for the East/West Line. These cars will be placed in service beginning in 1984. Seven of the 20 kilometers of the East/West Line are now complete and ridership has reached 400,000 passengers daily using existing North/South Line cars. It is expected to top 1.5 million per day when complete.

The Sao Paulo system is now carrying over 1.2 million passengers daily and operates 19 hours each day, 7 days a week. It carries 12 million passengers per kilometer, compared with 2.8 million for the New York Subway System and 1.4 million for the London Transportation system.

Since the start of revenue service in 1974, the Sao Paulo Metro has provided superior performance. Today it rates among the best fully automated systems in the world. Availability of all trains during peak hours of revenue service is greater than 98 percent.

The data gathered has monitored achieved regeneration of the Westinghouse chopper equipment at Sao Paulo and indicates that significant energy savings have been realized. Before examining these data, it will be useful to briefly review the characteristics and limitations of the chopper regeneration phenomenon.

CHARACTERISTICS AND LIMITATIONS

Regeneration in transit applications describes the process wherein the kinetic energy of the vehicle during a braking cycle is converted to electrical energy by operating the motors as generators, thereby returning electrical energy to the line. The desirability of using regenerative braking to conserve power has been heightened in recent years by increased emphasis on reducing energy consumption.

The application of chopper control for traction motors has made regeneration technically and economically feasible. Regeneration is essentially an inherent capability of the chopper requiring only minor additions to logic and control to include regeneration capabilities once a dynamic braking circuit has been established.

The magnitude of achievable regeneration is widely misunderstood and is often credited with the ability to save 50 percent of system energy. While this is theoretically possible under ideal conditions, three primary factors inhibit the energy ability of the chopper below this theoretical limit.

The first and most important is the fact that chopper control can only regenerate the amount of kinetic energy which is stored in the car at the moment braking begins. This is slightly reduced by the energy used in overcoming train resistance and I^2R losses of the motors and motor circuitry. The resulting amount of available energy is a function of several variables including station spacing on the system, weight of the car, and the speed of the car when braking begins.

The second inhibiting factor is that full regeneration cannot occur when the traction motor generated voltage is higher than the system third rail line voltage. This situation can occur at high speeds depending on the amount of braking needed and requires that the part of the generated voltage which is above the line voltage be absorbed by resistors on the car and not be regenerated.

The third factor which inhibits the energy savings of the chopper relates to the concept of line receptivity. This is a measure of how much returned or regenerated energy can be absorbed by the system.

Line receptivity is a dynamic factor which is limited by system line voltage conditions and their factors such as:

1. Allowable voltage at the regenerating train
2. Accelerating rate and speed of the load trains (KW demand)
3. Operating headways
4. Spacing of power substations
5. Spacing of passenger stations
6. Regenerated power
7. Third rail resistance
8. Auxiliary loads
9. Wind velocity
10. Rail sectionalization

All of these vary greatly and are almost never ideal simultaneously. In addition, the actual time in braking when regeneration is possible and the time when trains draw maximum power is a small percentage of the total run time in normal operation. In order to maximize the effective use of regeneration, the receiving trains have to draw maximum power at that instant.

Analyses using computer simulations of existing transit systems have shown that 100 percent line receptivity is possible on large transit systems like Sao Paulo only a small percentage of the system operating time. These analyses indicate expected receptivity to average 40 to 50 percent.

Other studies conducted on a full-time, system-wide basis, however, have indicated that chopper regenerative braking can save as much as 20 percent of the energy required by a typical rapid transit system. The following data from Sao Paulo on regeneration achieved support these conclusions.

DATA ANALYSIS

Table I shows actual traction power consumption as collected from the monthly statements of Servicos de Electricidade, S.A., the electric utility supplying the Sao Paulo Metro. The data cover the 6 year period from January, 1977 through December, 1982, including approximately 155 million car-kilometers (100 million car-miles) of operation. The table shows the actual kilowatt-hours of electricity consumed each month during this period, totaling over 550 million kilowatt-hours.

The calculated average number of trains in commercial operation by month is shown in Table II. These values are obtained by determining total train-hours and dividing by the total number of operating hours of the system.

Prior to 1977, trains were not corrected for regeneration. As circuit modifications were made, the number of trains equipped with regeneration capability increased until all trains were equipped by December , 1977. Table III indicates the number of regenerating trains on the system through December, 1979. After staying at the December, 1977 level of 31 throughout 1978, the number of trains in regeneration increased through 1932 due to the placement of new cars in service ordered since 1977.

Figure 2 shows a composite graph of the three sets of data reviewed in the tables. The solid line plots traction energy consumed, the dashed line shows the average trains in service, and the dotted line shows the actual trains in regeneration. The variations in energy consumption by month are a function of several exogenous factors such as special training programs to Metro personnel, special preventive maintenance programs, number of operating days in the month, and , in 1979, the additional power requirements associated with system testing and check-out of new cars on the system. The existence or absence of any one of these factors can increase or decrease system power consumption in any particular month.

Without these extraordinary effects, the solid line showing energy consumed would slope continuously downward from February, 1977 to January, 1978. This portion of the curve indicates a trend of energy savings by the increased use of regeneration on the Sao Paulo system.

This trend was examined more closely by looking further at the total car-kilometers traveled, by month, with regeneration and without regeneration as shown in Table IV. Simply adding the two sets of figures in the table shown for 1977 yields the total car-kilometers traveled on the system during that year. The right-hand column for the years 1978 through 1982 is zero since all trains operated with regeneration after that time.

From these data, the kilowatt-hours consumed on the system per car-kilometer by month were calculated, shown in Table V. The kilowatt-hours consumption data shown in Table I were divided by the total car-kilometers traveled shown in Table IV, with and without regeneration, on the system by month.

Plotting this calculation against the actual number of trains in regeneration shown by the dotted line on Figure 3 reveals a clearer picture of the trend developing.

It is clear from these curves that a significant trend was established during 1977 of decreasing energy consumption as additional regenerative capability was introduced into the system. To estimate the power savings reflected during that year, a simple linear regression curve was calculated for the kilowatt-hour per car-kilometer data points as shown on Figure 4. Using this curve, it was calculated that the Sao Paulo Metro realized an actual savings in power delivered to the third rail of 18.2 percent over the 12 months from January, 1977 through December, 1977. This savings is actually greater than 20 percent of the power used for traction. Similar regression curves have been calculated for the years 1978 and 1979 which show an even further, yet much smaller decline in power delivered in the neighborhood of 4-5 percent.

This experience in Sao Paulo has dramatically proven that chopper regenerative braking can save more than 20 percent of the energy required by a typical rail rapid transit system. As further data become available over the next several years from properties such as the Sao Paulo Metro, we expect their collective experience will demonstrate even more conclusively that the regenerative capability of chopper control can mean many operating dollars saved on modern rail transit systems.

ELECTRICAL ENERGY CONSUMED (KWH)

1977

Jan. = 7,004,000
Feb. = 6,568,000
Mar. = 7,390,000
Apr. = 6,354,000
May = 6,908,000
Jun. = 6,726,000
Jul. = 7,018,000
Aug. = 7,114,000
Sep. = 6,669,000
Oct. = 7,036,000
Nov. = 6,389,000
Dec. = 6,073,000

Total 1977 = 81,249,000

1978

Jan. = 6,192,000
Feb. = 6,122,000
Mar. = 6,528,000
Apr. = 6,581,000
May = 6,696,000
Jun. = 6,120,000
Jul. = 6,448,000
Aug. = 6,324,000
Sep. = 6,061,000
Oct. = 6,510,000
Nov. = 6,180,000
Dec. = 6,820,000

Total 1978 = 76,582,000

1979

Jan. = 6,572,000
Feb. = 5,544,000
Mar. = 7,316,000
Apr. = 6,780,000
May = 7,378,000
Jun. = 6,720,000
Jul. = 7.254,000
Aug. = 7,254,000
Sep. = 6,000,000
Oct. = 6,758,000
Nov. = 6,840,000
Dec. = 7,564,000

Total 1979 = 81,980,000

Table I

1980

Jan. = 7,105,519
Feb. = 6,687,335
Mar. = 7,286,523
Apr. = 6,929,778
May = 7,225,016
Jun. = 7,169,502
Jul. = 7,415,525
Aug. = 7,093,559
Sep. = 7,138,424
Oct. = 7,492,321
Nov. = 7,063,456
Dec. = 7,719,831

Total 1980 = 86,326,789

1981

Jan. = 7,514,798
Feb. = 6,675,368
Mar. = 7,398,423
Apr. = 7,148,447
May = 7,728,427
Jun. = 7,659,416
Jul. = 8,254,923
Aug. = 8,700,309
Sep. = 9,776,545
Oct. = 9,518,418
Nov. = 9,623,052
Dec. = 10,372,396

Total 1981 = 100,370,522

1982

Jan. = 9,779,200
Feb. = 9,070,100
Mar. = 10,177,900
Apr. = 9,667,300
May = 10,990,400
Jun. = 10,765,800
Jul. = 10,998,500
Aug. = 11,061,900
Sep. = 10,684,700
Oct. = 10,699,000
Nov. = 10,699,900
Dec. = 11,233,400

Total 1982 = 125,828,100

Table I

AVERAGE TRAINS IN COMMERCIAL OPERATION

$$\left[\frac{\text{Total Train-Hours}}{\text{Total Operation Hours}}\right]$$

1977

Jan. = 19
Feb. = 19
Mar. = 19
Apr. = 21
May = 21
Jun. = 21
Jul. = 22
Aug. = 22
Sep. = 22
Oct. = 22
Nov. = 22
Dec. = 22

1978

Jan. = 23
Feb. = 23
Mar. = 23
Apr. = 23
May = 23
Jun. = 23
Jul. = 23
Aug. = 23
Sep. = 23
Oct. = 23
Nov. = 23
Dec. = 23

1979

Jan. = 24
Feb. = 24
Mar. = 24
Apr. = 24
May = 24
Jun. = 24
Jul. = 24
Aug. = 24
Sep. = 24
Oct. = 24
Nov. = 24
Dec. = 24

1980

Jan. = 24
Feb. = 24
Mar. = 24
Apr. = 24
May = 24
Jun. = 24
Jul. = 24
Aug. = 24
Sep. = 24
Oct. = 24
Nov. = 24
Dec. = 24

Table II

1981

Jan. = 27
Feb. = 27
Mar. = 27
Apr. = 27
May = 27
Jun. = 27
Jul. = 27
Aug. = 27
Sep. = 27
Oct. = 27
Nov. = 27
Dec. = 27

1982

Jan. = 34
Feb. = 34
Mar. = 34
Apr. = 34
May = 34
Jun. = 34
Jul. = 34
Aug. = 34
Sep. = 34
Oct. = 34
Nov. = 34
Dec. = 34

Table II

TRAINS IN REGENERATION

1977

Jan. = 1
Feb. = 1
Mar. = 5
Apr. = 7
May = 11
Jun. = 13
Jul. = 18
Aug. = 22
Sep. = 26
Oct. = 29
Nov. = 29
Dec. = 31

1978

Jan. = 31
Feb. = 31
Mar. = 31
Apr. = 31
May = 31
Jun. = 31
Jul. = 31
Aug. = 31
Sep. = 31
Oct. = 31
Nov. = 31
Dec. = 31

1979

Jan. = 33
Feb. = 34
Mar. = 35
Apr. = 36
May = 37
Jun. = 37
Jul. = 37
Aug. = 37
Sep. = 37
Oct. = 37
Nov. = 37
Dec. = 38

1980

Jan. = 38
Feb. = 38
Mar. = 38
Apr. = 38
May = 38
Jun. = 41
Jul. = 41
Aug. = 41
Sep. = 41
Oct. = 41
Nov. = 41
Dec. = 41

1981

Jan. = 41
Feb. = 41
Mar. = 41
Apr. = 41
May = 41
Jun. = 41
Jul. = 41
Aug. = 41
Sep. = 41
Oct. = 44
Nov. = 47
Dec. = 49

Table III

1982

Jan. = 50
Feb. = 50
Mar. = 50
Apr. = 50
May = 50
Jun. = 50
Jul. = 50
Aug. = 50
Sep. = 50
Oct. = 51
Nov. = 51
Dec. = 51

Table III

CAR-KILOMETERS TRAVELED

1977

With Regeneration		Without Regeneration
Jan.	20,508	1,800,594
Feb.	53,388	1,551,802
Mar.	146,778	1,662,396
Apr.	305,346	1,486,390
May	539,664	1,225,086
Jun.	713,920	1,257,004
Jul.	947,250	919,424
Aug.	1,236,660	692,888
Sep.	1,460,040	359,564
Oct.	1,689,432	211,548
Nov.	1,702,386	118,808
Dec.	1,902,954	28,144

1978

With Regeneration		Without Regeneration
Jan.	1,901,210	0
Feb.	1,737,042	0
Mar.	1,904,652	0
Apr.	1,916,550	0
May	2,182,626	0
Jun.	1,772,196	0
Jul.	1,764,678	0
Aug.	1,756,860	0
Sep.	2,141,538	0
Oct.	2,161,884	0
Nov.	1,787,490	0
Dec.	1,803,564	0

1979

With Regeneration		Without Regeneration
Jan.	1,690,788	0
Feb.	1,741,218	0
Mar.	2,372,490	0
Apr.	1,927,848	0
May	1,946,658	0
Jun.	2,435,490	0
Jul.	1,969,170	0
Aug.	1,935,120	0
Sep.	2,416,836	0
Oct.	1,882,788	0
Nov.	2,223,612	0
Dec.	2,051,724	0

Table IV

1980

With Regeneration		Without Regeneration
Jan.	1,969,647	0
Feb.	1,845,236	0
Mar.	1,966,172	0
Apr.	1,880,148	0
May	1,961,424	0
Jun.	1,873,098	0
Jul.	2,019,775	0
Aug.	2,109,738	0
Sep.	2,100,117	0
Oct.	2,173,025	0
Nov.	2,045,767	0
Dec.	2,211,595	0

1981

With Regeneration		Without Regeneration
Jan.	2,109,200	0
Feb.	1,926,200	0
Mar.	2,097,656	0
Apr.	2,037,724	0
May	2,127,516	0
Jun.	2,085,792	0
Jul.	2,214,981	0
Aug.	2,226,834	0
Sep.	2,326,301	0
Oct.	2,355,329	0
Nov.	2,448,575	0
Dec.	2,671,119	0

1982

With Regeneration		Without Regeneration
Jan.	2,537,615	0
Feb.	2,281,797	0
Mar.	2,624,696	0
Apr.	2,517,796	0
May	2,893,840	0
Jun.	2,894,045	0
Jul.	2,956,472	0
Aug.	2,957,714	0
Sep.	2,860,629	0
Oct.	2,903,749	0
Nov.	2,856,931	0
Dec.	3,019,130	0

Table IV

KWH PER CAR-KILOMETER

1977

	KWH		Car-Kilometers		
Jan.	7,004,300	÷	1,821,102	=	3.846
Feb.	6,567,700	÷	1,605,190	=	4.092
Mar.	7,390,200	÷	1,809,174	=	4.085
Apr.	6,353,600	÷	1,791,736	=	3.546
May	6,907,800	÷	1,764,750	=	3.914
Jun.	6,726,000	÷	1,970,924	=	3.413
Jul.	7,017,600	÷	1,866,674	=	3.759
Aug.	7,113,600	÷	1,929,548	=	3.687
Sep.	6,669,200	÷	1,819,604	=	3.665
Oct.	7,036,000	÷	1,900,980	=	3.701
Nov.	6,388,788	÷	1,821,194	=	3.508
Dec.	6,072,820	÷	1,931,098	=	3.145

1978

	KWH		Car-Kilometers		
Jan.	6,192,000	÷	1,901,210	=	3.257
Feb.	6,122,000	÷	1,737,042	=	3.524
Mar.	6,528,000	÷	1,904,652	=	3.427
Apr.	6,581,000	÷	1,916,550	=	3.434
May	6,696,000	÷	2,182,626	=	3.068
Jun.	6,120,000	÷	1,772,196	=	3.453
Jul.	6,448,000	÷	1,764,678	=	3.654
Aug.	6,324,000	÷	1,756,860	=	3.600
Sep.	6,061,000	÷	2,141,538	=	2.830
Oct.	6,510,000	÷	2,161,884	=	3.011
Nov.	6,180,000	÷	1,787,490	=	3.457
Dec.	6,820,000	÷	1,803,564	=	3.781

1979

	KWH		Car-Kilometers		
Jan.	6,572,000	÷	1,690,788	=	3.887
Feb.	5,544,000	÷	1,741,218	=	3.184
Mar.	7,316,000	÷	2,372,490	=	3.084
Apr.	6,780,000	÷	1,927,848	=	3.517
May	7,378,000	÷	1,946,658	=	3.790
Jun.	6,720,000	÷	2,435,490	=	2.759
Jul.	7,254,000	÷	1,969,170	=	3.684
Aug.	7,254,000	÷	1,935,120	=	3.749
Sep.	6,000,000	÷	2,416,836	=	2.483
Oct.	6,758,000	÷	1,882,788	=	3.589
Nov.	6,840,000	÷	2,223,612	=	3.076
Dec.	7,564,000	÷	2,051,724	=	3.687

Table V

1980

	KWH		Car-Kilometers		
Jan.	7,105,519	÷	1,969,647	=	3.608
Feb.	6,687,335	÷	1,845,236	=	3.624
Mar.	7,286,523	÷	1,966,172	=	3.706
Apr.	6,929,778	÷	1,880,148	=	3.686
May	7,225,016	÷	1,961,424	=	3.684
Jun.	7,169,502	÷	1,873,098	=	3.828
Jul.	7,415,525	÷	2,019,775	=	3.672
Aug.	7,093,559	÷	2,109,738	=	3.362
Sep.	7,138,424	÷	2,100,117	=	3.399
Oct.	7,492,321	÷	2,173,025	=	3.448
Nov.	7,063,456	÷	2,045,767	=	3.452
Dec.	7,719,831	÷	2,211,595	=	3.490

1981

	KWH		Car-Kilometers		
Jan.	7,514,798	÷	2,109,200	=	3.562
Feb.	6,675,368	÷	1,926,200	=	3.465
Mar.	7,398,423	÷	2,097,656	=	3.526
Apr.	7,148,447	÷	2,037,724	=	3.508
May	7,728,427	÷	2,127,516	=	3.632
Jun.	7,659,416	÷	2,085,792	=	3.672
Jul.	8,254,923	÷	2,214,981	=	3.726
Aug.	8,700,309	÷	2,226,834	=	3.907
Sep.	9,776,545	÷	2,326,301	=	4.202
Oct.	9,518,418	÷	2,355,329	=	4.041
Nov.	9,623,052	÷	2,448,575	=	3.930
Dec.	10,372,396	÷	2,671,119	=	3.883

1982

	KWH		Car-Kilometers		
Jan.	9,779,200	÷	2,537,615	=	3.853
Feb.	9,070,100	÷	2,281,797	=	3.974
Mar.	10,177,900	÷	2,624,696	=	3.877
Apr.	9,667,300	÷	2,517,796	=	3.839
May	10,990,400	÷	2,893,840	=	3.797
Jun.	10,765,800	÷	2,894,045	=	3.719
Jul.	10,998,500	÷	2,956,472	=	3.720
Aug.	11,061,900	÷	2,957,714	=	3.740
Sep.	10,684,700	÷	2,860,629	=	3.735
Oct.	10,699,000	÷	2,903,749	=	3.684
Nov.	10,699,900	÷	2,856,931	=	3.745
Dec.	11,233,400	÷	3,019,130	=	3.720

Table V

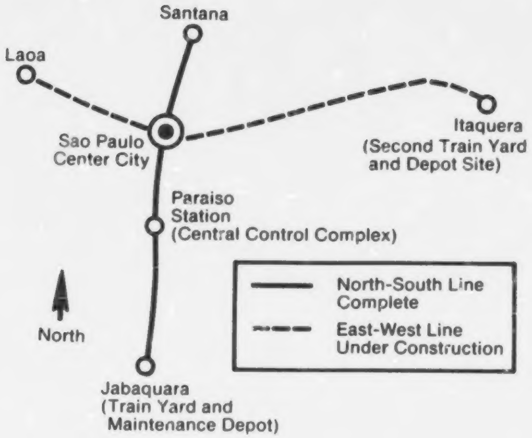
Santana
Laoa
Sao Paulo Center City
Itaquera (Second Train Yard and Depot Site)
Paraiso Station (Central Control Complex)
North
North-South Line Complete
East-West Line Under Construction
Jabaquara (Train Yard and Maintenance Depot)

Figure 1

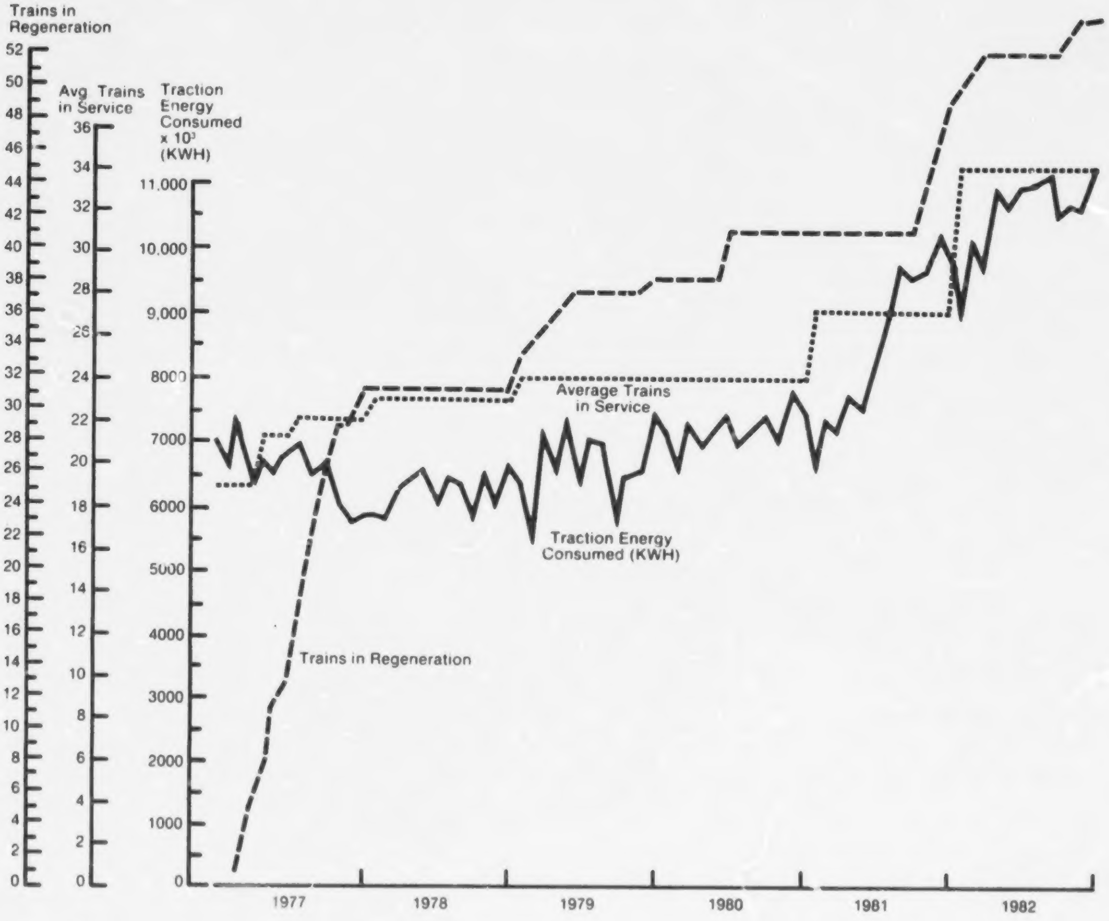
Trains in Regeneration
52
50
48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
Avg. Trains in Service
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
Traction Energy Consumed x 10³ (KWH)
11,000
10,000
9,000
8000
7000
6000
5000
4000
3000
2000
1000
0
Average Trains in Service
Traction Energy Consumed (KWH)
Trains in Regeneration
1977
1978
1979
1980
1981
1982

Figure 2

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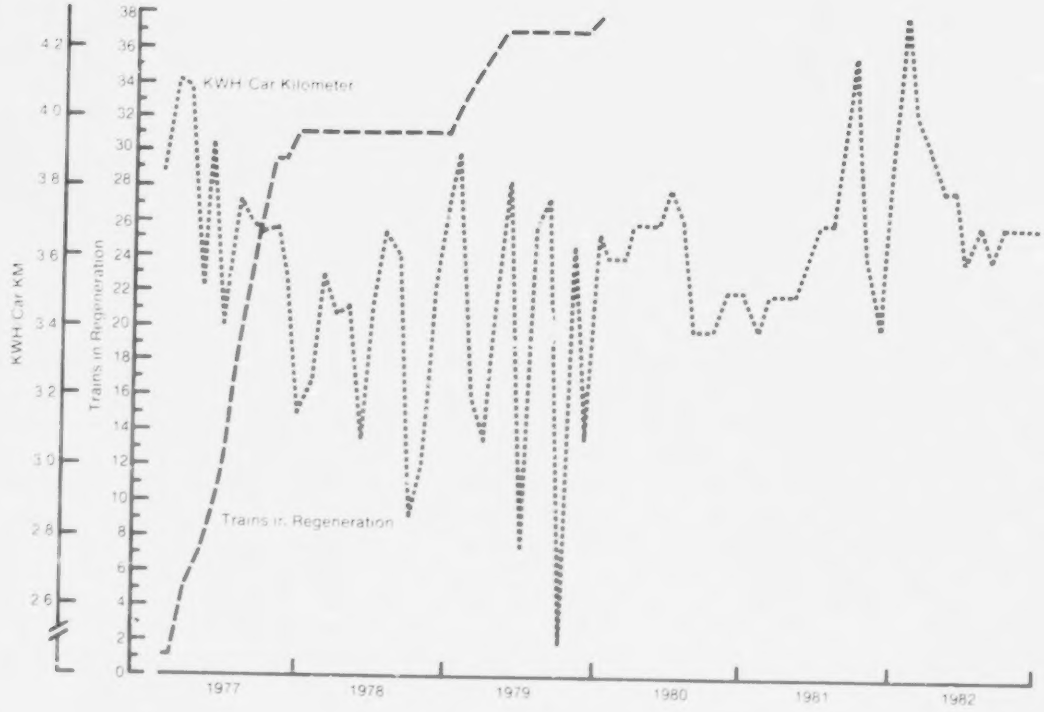

4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
KWH Car KM
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
Trains in Regeneration
KWH Car Kilometer
Trains in Regeneration
1977
1978
1979
1980
1981
1982

Figure 3

2.46

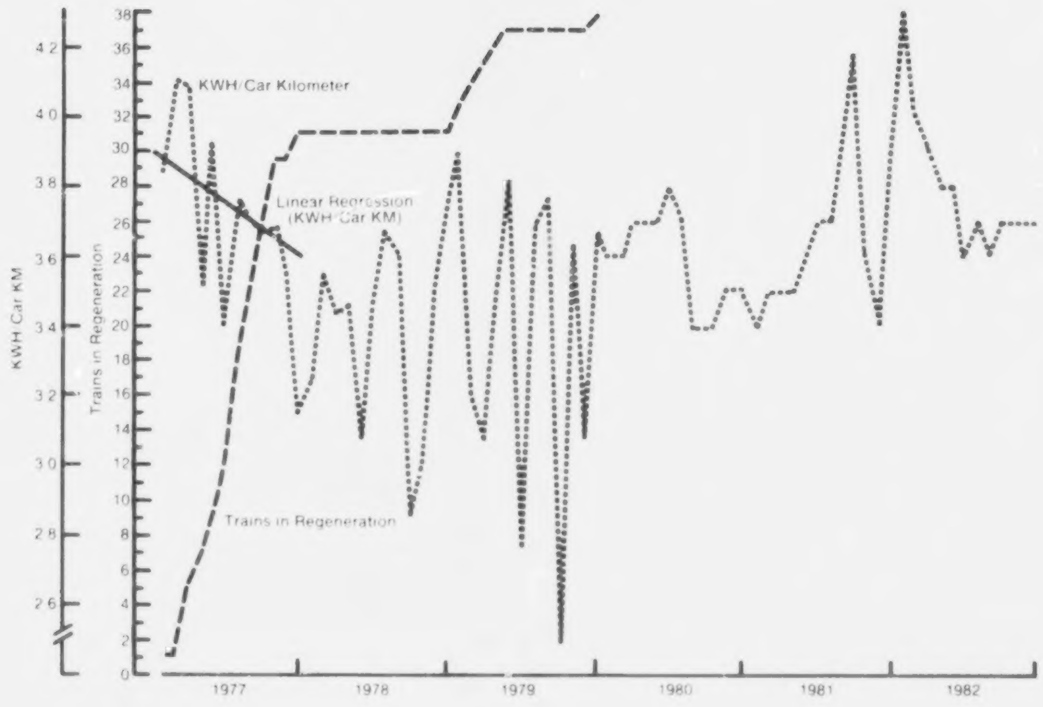

KWH Car KM
4.2
4.0
3.8
3.6
3.4
3.2
3.0
2.8
2.6
Trains in Regeneration
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
KWH/Car Kilometer
Linear Regression
(KWH Car KM)
Trains in Regeneration
1977
1978
1979
1980
1981
1982

Figure 4

PANEL SESSION

"BARRIERS TO THE INTRODUCTION OF NEW TECHNOLOGY IN BUS OPERATIONS"

Moderator: *John Aurelius, Asst. Chief Engineer - Projects, New Jersey Transit Rail Operators*

Panel Members:

Franz Gimmler, Deputy Assoc. Admin. of Technology, U.S. DOT/UMTA
George Pickett, Manager, Transit Sales, M.A.N. Truck and Bus
John Wilkins, Director of Operations Planning, New Jersey Transit Bus Operations
Mike Buckel, Engineering Dir. Bus and Automotive Engineering, Booz, Allen & Hamilton
Arthur Schwartz, Chase, Rosen & Wallace Inc.
Wayne Diggs, Superintendent, Maintenance and Purchasing, Golden Gate Bridge Highway and Transportation District.

The introduction of new vehicles and components into the transit bus operation industry is difficult. The difficulty may be due to some of the following:

1. High initial cost of new technology, although life cycle costs may be lower.

2. Problems experienced with new technologies due to lack of thoroughness in design, prototyping and workmanship.

3. New Maintenance requirements that transit operators are not prepared or equipped for.

4. Difficulty in measuring the benefits and costs of new technologies. Some technologies introduced may have been of questionable value.

5. A transit organizational structure concerned with operating needs and not designed to respond to demonstration projects.

6. Inadequate marketing by the manufacturers.

7. Incorrect Federal decisions on which technologies to fund and the level of support to provide.

The panel will discuss various barriers and will examine means by which these barriers may be overcome.

MR. AURELIUS:

First off, I would like to welcome those of you who are here and those who are yet to come to the Bus Panel. I suppose I should pull out the program and read the correct title -- "Barriers to the Introduction of New Technology into Transit Bus Operations."

My name is John Aurelius. I work for New Jersey Transit Rail Operations, Inc., which means that I'm employed by the commuter railroad in New Jersey. We have three (3) different divisions -- the headquarters, a bus company and a railroad company. I work for the railroad company. So here I am chairing a bus panel which, did cause some consternation among the leadership in New Jersey -- Why was someone from the railroad being invited to speak on buses? But, I don't regard this as really a bus subject, and I'll get into that when I get into my own speech.

I have a fairly large panel here -- large partly in the fact that it is very distinguished, partly in the fact that it's large in size. We will try to keep our presentations brief so there will be time for some questions and answers because I think this is a fantastic discussion subject. It is something that I am sure everybody in the room has some opinion on, and I hope we can get a lot of those opinions out in some give-and-take.

From my left, the first member of the panel is Arthur Schwartz. Arthur has a Master's in City Planning from the University of Pennsylvania. He has been involved in transportation planning projects for Chase, Rosen, and Wallace, a consulting firm, since 1973. He was formerly with New Jersey D.O.T., the Tri-State Regional Planning Commission, which of course is now defunct, and Pennsylvania D.O.T. George Pickett is a native of Vicksburg, Mississippi. He has a Bachelor of Science in Civil Engineering from Mississippi State University in 1976, joined the Trane Company as Sales Engineer of Bus Air

Conditioning and later became Product Manager for Bus Air Conditioning, joined M.A.N. Truck and Bus Corporation in December 1980 as Manager of Transit Sales. He is active on the Bus Technology Liaison Board and the APTA Procurement Committee. Wayne Diggs is the Superintendent of Maintenance and Purchasing at Golden Gate Bridge Highway and Transportation District, which has a multi-modal fleet including 300 buses, four high-capacity passenger ferries, Van Pool and club bus. Mr. Diggs has been with Golden Gate Transit since its inception 12 years ago. He has served on various APTA committees and is active as a consultant in his spare time.

Franz Gimmler is a man who needs no introduction and who was introduced last night. His home town is Milwaukee and he is a mechanical engineer from Yale University. He has been with UMTA since its origin in 1967, as part of H.U.D -- Housing & Urban Development. He has been Grants Officer, Demonstration Manager, Regional Administrator, and currently is the Deputy Associate Administrator of Technology, which is Research, Development, and Demonstration. Mike Buckel, who informs me that he is not Michael but Mike. Mike is the Engineering Director of Bus & Automotive Engineering projects at Booz, Allen & Hamilton. He has 12 years of experience in Transit Bus Engineering with Booz Allen, and previously was with the Chrysler Corporation for nine years. He has a B.S. in Mechanical Engineering from Washington University in St. Louis, and an M.S. in Automotive Engineering from the Chrysler Institute of Engineering. And over on my right is John Wilkins, Director of Operations Planning, New Jersey Transit Bus Operations, which is New Jersey's major bus operator. Mr. Wilkins has also participated in numerous studies dealing with the economics associated with trolley bus systems and trolley bus overhead construction. He has a B.S. in Civil Engineering from Carnegie-Mellon and a Master's in Business Administration from the University of Pittsburgh.

I'd like to set the stage with a few remarks and a little slide show on innovation. The barriers to innovation are common to bus and rail, with a major factor being the necessity of offering a reliable transportation service that the customer can count on all the time, and remember, those of us who are in transportation operations are serving nothing but customers, the people who have to get to work. The transit rider isn't there for a research project. He's trying to get to work or get home, or to get to a predictable place at a predictable time.

The slides illustrate several notable innovations in transportation -- notable but not necessarily all successful. My first slide is, I think, probably the biggest innovation that ever took place in transportation. It was replacing animal power with steam. This technology was not terribly successful in urban transportation because of the urban environment. Here is the very first subway -- I believe, in the world. This is the Wapping Station in London. I don't remember the name of the line, but this goes back well before the turn of the century and was originally operated with steam. The next innovation was to get the fire out of the vehicle, put it somewhere else, and the first way to do that was mechanically with a cable which was driven by a steam engine at some remote place. This was quite an expensive and difficult technology and it was rather quickly superseded, of course, by the electric technology which makes that connection between the prime mover and the transit vehicle considerably cheaper to build.

Then, of course, somebody figured out a way to build an engine in a vehicle that required neither tracks nor wire. The early motor bus was certainly a drastic innovation, but it took a long time for it to become really accepted by the major part of the transportation scene. Also, in parallel, there were early highway buses.

Coming into what I would call the modern era, a number of notable things took place in the 1930's. The GG-1 electric locomotive which was a milestone vehicle and just recently retired in New Jersey Transit. The PCC trolley car -- this is the very first one in service in Brooklyn, the very first production one -- had a number of important innovations; lightweight trucks, and a standard design which had never been around in railcars before. Then we got into somewhat more modern highway and transit buses. Of course, the transit bus was available both as a gas or electric vehicle at the time.

In the 1940's, the Swiss had a flywheel bus. Of course, we're working right now to see if that technology will come back in a modern version. This wasn't a great success, but that fleet did live out its lifetime -- about 50 vehicles. The major innovation in the 1950's, if you will forget, for the moment, the trolley poles on this vehicle -- was the diesel bus. The diesel engine is a great step ahead of the gasoline engine and while the diesel was available in buses as early as the very late 1930's it didn't really become very popular until the 1950's. This was a second generation dual propulsion vehicle in New Jersey. And, as a dual propulsion vehicle, this particular one did not go into a fleet use. It served its life as a diesel.

Another innovation of the 1950's was the RDC car, a self-propelled multiple-unit car for railroads. In the highway bus field, the Scenicruiser was a big step forward. It combined a number of things that had been on other buses before. Air suspension, which made the bus much more comfortable, a deck-and-a-half format which we now see extended all through the length of the highway bus, and the 40-foot length which this bus pioneered and it required some politicking in order to get it made legal.

Now, here's a bus that we're all familiar with. I can remember when this was the flakey new technology. Now, it's the good old jobs. The New Look bus. And it's been around a long time, and it's still around -- you'll see New Looks out in the street today.

A lot of people will call this a people mover. I don't. I call it a rubber-tired rapid transit system, this was the Westinghouse Sky Bus. Of course, it did not, in that form, attain the status of an operational system although a good number of airport systems and theme park systems have been built by Westinghouse, using this technology and there is, of course, finally, a system very similar to it now operating in Lyons, France.

This is the Metroliner car. Very, very fast, multiple-unit car for railroad, 150-miles-per-hour capability. The concept is still available, passing through Baltimore, practically every hour of the day. However, the Metroliner cars themselves were not particularly successful.

Here is the first trolley bus that was chopper equipped. Now, I should be very careful because there are fans in the room. This may not be the one, but it is a member of the fleet. This is in St. Gallen, Switzerland, and Brown Boveri was building prototype choppers as early as the mid-sixties.

Here is a battery powered bus and another battery powered bus in Germany, but I really put this slide up because it actually illustrates the German "PCC" bus, if you will. The PCC trolley car and this VOV style of bus are designs that were put together by industry committees and licensed to various manufacturers. Buses looking exactly like this are made by Daimler-Benz as well as M.A.N., and I believe by Kaessbohrer Setra and probably two other German manufacturers that escape me at the moment, but it is a transit industry standard.

In commuter rail, the push-pull train is an important innovation and quite a successful one in New Jersey. In the late 1960's, we had BART, the subway beautiful. And it is beautiful, and it works better than a lot of the press that it got. But it certainly was difficult to bring this much innovation into a rapid transit system that early.

Here is a 102-inch wide highway bus, the MC-6, and that wasn't terribly successful. It did not succeed in the political arena, and also wasn't a terribly good mechanical coach, I believe.

Here is a bus that isn't a bus. It's the Sea-bus that runs from Vancouver to North Vancouver and it's operated as a floating rapid transit system or what probably is the most innovative bus of all -- it does not carry automobiles, and the docking system that allows them to get in and out of the dock in less than two minutes.

This is the light rail vehicle, the successor to the streetcar, this particular one being a Boeing car which, of course, has been a mixed success. San Francisco likes it. Boston has had some problems with it.

Here's a modern interurban line, running from San Diego to the border with Mexico near Tijuana. And here's a very innovative locomotive that may be a successor to the GG-1, very high-speed, quite lightweight, very low-loading on wheels, not a very good puller. Certainly it isn't a freight locomotive, but today's Metroliner services are pulled by these locomotives and obtain schedule speeds as good as the MU cars have.

Here's a European innovation, the Renault SC-10, a lot of detailed differences between that and other buses that you might find around.

Here's a French trolley bus with a small diesel engine in it, for auxiliary propulsion. You want a big bus? Here's a big bus. A German firm, Neoplan, came into the U.S. scene and innovated by trying to build a non-innovative bus. I know I shouldn't say "try to build" -- this was a successful bid on a "new look" procurement for MARTA (the Atlanta transit system). MARTA wanted an older design bus and they got a brand new design. And I think they've been successful.

Here's another Neoplan product, a double-decker highway bus. And now, let's look at some small buses. This wasn't a terribly successful vehicle but they sold quite a few of them. The name of the firm was Highway Products, and I don't think they're in business today. I never heard of anybody who really liked to maintain one of these. A somewhat more successful small bus, the Orion, Canadian designed, was built for a while by a Greyhound subsidiary in the U.S.A., and I believe now imported from Canada again.

And a Neoplan little bus. I don't know whether they have ever sold any of those in the United States because certainly it is an interesting-looking concept.

Now, this was meant to be Trans Bus. I couldn't find any American Trans Bus slides, so here's the German Trans Bus, the S-80, a very low floor bus, just one step up into the aisle. It has very small tires, and the tires are probably the key item in a very low floor bus like this. The interior. The exterior, unlike the American Trans Buses and advanced design buses, has a rear window and, fundamentally, I guess the reason is that the Germans don't usually use air conditioning, so you don't need room for a condenser. Here are the American advanced design buses, the GM and Flxible. They have had something of a spot in history, both of them.

The wheelchair lift. Certainly a controversial subject. This particular one is made by Lift-U.

Articulated -- sort of a success story in innovation, and I had some part in it. Popular in Europe, going back at least into the sixties (1960s), trials in the United States by M.A.N., Volvo, and Ikarus, produced a very successful fleet of buses in Seattle made by M.A.N., partly in Germany and partly in M.A.N.'s new plant in North Carolina. This one is Icarus, Hungarian-made, represented by Crown Coach in Los Angeles.

Here's a Neoplan, and, would you believe, a GM New Look made in Canada? This is the German Duo-Bus which is certainly innovative and has not actually become part of a fleet. This is both battery and trolley. It has an automatic rewiring scheme where the trolley poles have little guides on them. They spread and rise, and they clap together and then rise again to the wire, and your diesel bus has become a trolley bus.

Here's the French trolley bus, the dual-powered bus that we heard about a great deal. It's being tested in Seattle. In trolley bus innovation, here's the first Swiss standard artic chopper-controlled bus, also available as a two axle bus.

The AM General trolley bus had a chopper control and because it was innovative, it went into a lot of testing in Seattle before it went into service. It's running about 24 hours a day here in the Queen Anne section of Seattle, loaded with sandbags, never going back to the barn because there wasn't any wire to get it back to the barn, so they just put another driver on it and kept running it. It didn't need fueling, after all.

This is an Edmonton coach built on the GM New Look, and this is a Flyer coach for Vancouver with Westinghouse control. The Edmonton coach has Brown Boveri controls, and Brown Boveri was the prime contractor.

What I wanted to really illustrate are three different procurements of trolley buses in the North American area within a couple of years of each other, and the three different technologies for a very tiny market. The trolley bus was reinvented and reinvented.

I have just a couple of slides now on methods. One of them is the bus locator, which is a technology that's been coming real soon now, for a long time. I don't know of anybody who has a city-wide installation, but New York City has one garage in Queens equipped. This actually is a color display but it just happened I had black-and-white film. Certainly the busway is a very important concept. As far as I know, Pittsburgh has one of the very few pure busways in the United States -- and when I say "pure," I mean as opposed to a reserved lane on a freeway. These are roads that were actually built by the transit company and the Transit Authority controls who may use the road.

I think the Roadeo is an important innovation in operations, etc., the way of building driver-training and driver -- spirit. Also, providing information to passengers is an important function. This is a Solari split flap sign where the signs are actually painted on to little pieces of plastic that are mechanically moved, and this is a CRT display that shows the same kind of information.

I've tried to do this as a way of setting the stage, and I'd now like to turn the floor over to the panel. I'll start out with Franz Gimmler. Franz?

MR. GIMMLER:

Thank you, John. That was a very delightful introduction to the subject today, a very unusual collection of slides, and I appreciate the effort you went through in putting it together.

You spoke about innovation. Let me talk about barriers. I don't have any slides. But, let me try anyway, without slides, to talk about barriers to the introduction of the new technology.

The title suggests or invites a list, and I normally avoid lists, but in this case, I think it is going to be useful. I'd like to list what I think are the barriers. That's the simplest way of organizing what's obviously a very complex subject and also there may be structural vocabulary in the way of looking at barriers. I'd like to follow a listing of the barriers with a discussion of what we might do about the barriers, if anything, and I'd like to forewarn you that the listing is fairly random and is quite personal in terms of my perceptions. It's broad and also transit-specific and it's kind of loose. I don't mean to be provocative as well as responsible in talking about these barriers. So, let me start. There are nine of them that I've seen. You can probably add to that list. I think one of the first barriers, something that we're obviously experiencing right now, is a slow or depressed economy. There are low confidence levels in future markets. There is pessimism on the part of entrepreneurs and people who might be developing new technology, just an overall pall in the world of innovation.

I think the next barrier that I might list is specific to an industry and I think appropriate and relevant to transit in particular. That's the feeling that the history and success of innovation in the industry gives to the participants in the industry about further innovation. I think that the VCR or the autofocus cameras are very tough and very special technologies that the market might be leery of, but the Japanese history of success, the confidence that they have engendered in the market on their technological electronic products has instilled a trust, and our experience leads us to participate in an innovative market.

Transit, on the other hand, has faced many failures and problems when innovative, and I think that lends a general barrier throughout the transit industry to the idea of technological innovation.

I think the de-centralized industry is another factor and a barrier to innovation. How much technology transfer do we get in the oil industry because a lot of the big corporations are in Houston, or in the movie industry because the big producers are in Hollywood -- or the steel industry because they are located in Pittsburgh. And how many barriers do we face because we have one member of our industry in every city, scattered about the country? I think the size of the market is an obvious barrier to innovation.

The supplier or the venture capitalist has to look at how many units he can sell. If he can't sell many units, the financial equation that he has to undertake does not turn out to be a very favorable one if his market is too small.

Procurement procedures have to interface between the supplier and the buyer. Procurement procedures are, in general, the barrier in transit. In particular, there is a pattern due to procedures that allows the buyer to judge comfortably, among technological alternatives in order to pick something new. Do the procurement procedures allow him to pay extra for that newness?

As for leadership, I think we all, as leaders, have to take responsibility for either encouraging or discouraging technological innovation. Who of us sees the future? Who of us relates new technology to the vision that we have? Who speaks out? Who follows on a trail of a John Volpe or an Ed Anderson? These are people with whom you may not agree in terms of their vision, but they had a vision and promoted it.

Where is that person today speaking out? Is there somebody in APTA? Is there somebody in RPI? Is there somebody in UMTA? I think leadership has to be seen as a facilitator or a barrier of new technology.

Who are the agents of change? Are they a barrier at the point of purchase? The procurement agent, the responsible buying official in the transit agency -- what is his incentive? What is his performance norm? What is his boss and his board doing to encourage or discourage him to utilize new technology in solving problems?

Then there is the other side of the market table -- the bargaining table -- the product development director, the marketing manager. How does he perceive the receptiveness of the buyer? How willing is he to put himself into the shoes of the buyer and encourage him to innovate because he, the seller, knows of the advantages of the new technology?

And, finally, what about Government involvement? Is it supportive? Does it provide morale support? Does it provide financial support? Is it a very important contributor to the facilitation of new technology or is it a barrier to technology? When and where does it intervene? Does it facilitate when it intervenes? Or does it just distract and confuse? Is it consistent? Is there a role for the federal government? Is there a role for state government, or is there no role at all?

Those are nine barriers that I see in the deployment of new technology. In reflecting on them, I was not encouraged. I would say that the current condition of each is not conducive to new technology and it is not supportive. It's not positive.

I think all of us in this room believe that something should be done I don't think it takes any real visionary to see the role of new technology in solving immediate problems today.

Let me go through a quick list of what might be some issues with respect to each barrier and then address the overcoming of that barrier, if indeed technology and new technology have a role.

I spoke about economic conditions. My first impulse was to say, "Well, there's nothing we can do about those." But there is. We can vote in November. At least that's what we can do about the general economic conditions in the country.

As far as the experience in new technology, we must discover what about the transit experience in particular has led us to be, as an industry, somewhat distrustful of new technology? First of all, we've got to recognize that bleak history. Then we have to insist on the very highest standards. We have to test and test and test -- and then test again to be sure that what we're introducing is going to meet the very rigorous demands of this very special industry, and avoid an overconfidence. It's going to be difficult, over the long haul, to avoid and overcome the perception that new technology is not particularly helpful to the urban mass transportation industry. We've got to test before. We've got to test after, over, under. We have to do it in labs, in test tracks, and we have to set our demands and criteria very high because the industry requires it.

What can we do about the centralized industry? We can convene at conferences. We can write reports and prepare briefs. We can include the private sector in our communication, our outreach and our networking and we can include new technology. We can learn to use helicopters, electronic mail, networking, and other techniques to bring us together so that we are informed of new technologies and its benefits and we feel a part of the new technology world.

What can we do about the size of the market? We can't lose sight of that very precious market, however small in the United States, but I think we can try to apply a wide-angle lens to keep it in focus, but see what's in the peripheral areas of our vision that may be ignored at times. We can learn more about the off-shore market. We can learn more about the national activities offshore in technology innovation. We can reach out within our own borders and look at the airline industry, for instance, in terms of the dynamic maintenance concept applicable to transit. We can look to our fellow federal and state agencies. D.O.E. has a great deal to teach us as does the Defense Department. We can look to the trucking industry and we can look to high- speed rail. All of these are partners and their technologies can be associated and can be transferred to our smaller world.

As to the size of the market and the other side of that coin -- how can we spread our R&D dollars? Can we get together in consortiums or joint ventures to share the cost? We don't have such high costs to distribute over our small market.

In regard to procurement procedures, I think the federal government has done what it can. It has dropped the barriers. There are still local and state barriers and we all have to learn how better to use negotiated competitive procurement in pursuing the new technology and to make that procurement decision by the procurement agent a comfortable one.

Leadership? There are leaders among us. I think we have to encourage and support them. Often they feel lonely without that support. I was reminded of a visit last week out to Portland, Oregon, with an innovator in self-service fare collection. They are feeling very lonely and can see no national purpose -- all they can see is the cost of that innovation to them. And without our support, morally, and in this particular case, financially, they cannot carry the burden of innovation. I think all of you can probably think of examples of innovators with whom because of moral and financial support, we'll all be better off and I say that support is very definitely at the policy and political level as well as the technological one.

I was just reminded of FRA's position on high-speed rail. They are lending all kinds of moral support to the technology challenge of high-speed transportation in the United States. They're not putting a penny into it. And I want to emphasize that we all can support, with moral support, as well as financial support.

Finally, the change agent? The buyer? The seller? We can help them by quantifying the methods of new technology, not just by saying it's new technology and therefore it's good. But we can say it's new technology and it'll do this for you, or that. Get the information to their transit boards. I think technology innovation is too important. It's got financial considerations. It's got risk considerations. It's got trade-offs between capital, operating, and maintenance costs. These are matters that are the proper subject of board deliberation. Include the policy people as well as the technical people in the innovative process.

We also have to reward the product developers and marketing directors. We've got to reward them for their product innovation through financial means, life-cycle costs, other techniques -- to pay them extra for what they're giving us.

Finally, government involvement -- again, a subject covered by Carroll last night. Are the federal programs directed at the purchaser or at the supplier? At this point, they're really focused on both. I think we went through a phase where we were looking at technology pull-push, and working with the supplier. Unfortunately, we set our objectives too far into the future. We're worried about two-second headways and we delivered the product and industry said, "We don't need it." We swung to the other side, felt that we should support the operators with technical assistance -- a wonderful concept and yet often we're called in to solve the problems when it's too late.

The marketplace hasn't solved it. The operator comes to us about problems that we should have started working on two or three years earlier. Either it's insoluble or we give it superficial, "band-aid" treatment.

I feel that the role of the federal government should be reoriented. We should start to work more closely with the supply industry. We cannot lose track of these operators. We cannot lose track of the bus technology liaison board. We cannot lose that touch with APTA, but at this point, we might be doing a better service for technology innovation if we, in the federal government, reoriented our efforts and worked more closely with the supply industry.

So, those are some of my thoughts -- nine barriers -- and some responses to those barriers. I thank you very much for your attention. I enjoyed discussing this very important subject with you.

MR. PICKETT:

I appreciate the opportunity to share my thoughts with this distinguished group of transit industry representatives. As Manager of Transit Sales for M.A.N. Truck & Bus Corporation, I feel I have gained significant experience in the subject matter of this session -- Barriers to the Introduction of New Technology in Bus Operations.

M.A.N. has successfully introduced the articulated transit bus, M.A.N. diesel engines, M.A.N. axles, M.A.N. suspension, RENK transmission, and more to today's U.S. transit industry. And, soon, we will take another major step and introduce our new 40-foot transit bus in October at Expo '84.

I'd like to begin by talking about the word "new." One of Webster's seven definitions is "different from one of the same categories as existed previously." The key word here is "different." Different implies change. Let's discuss change. I'd like each of you to cross your arms like this. Now, cross your arms again, but reverse the position like this. How does that feel? Try putting your hands together, fingers interlocked and thumbs overlapped, like this. Note which thumb is on top. And then put them together again so that the other thumb is on top, the other way. How does that feel?

For most of us, such a change from our normal habits makes us uncomfortable. What I'm trying to show is that change is uncomfortable, for most of us, whether changing the position in which we cross our arms, or changing what engine we use in our buses. New technology cannot be introduced without change. Change makes people uncomfortable and uncomfortable people are barriers. How do we overcome this barrier?

To successfully introduce new technology in bus operations, commitment is essential. This commitment must be from both the supplier and the operator. Lack of commitment from either is a sure way to cause failure of the introduction process. Suppose the operator, with or without the recommendations of the third-party consultant, specifies a new feature which the suppliers find uncomfortable. In the pre-bid process, the supplier is unsuccessful in getting that specific feature removed. Now the supplier must, in order to obtain the order, include this feature in the bid and provide it with the delivered product. This is the operator's decision, not the supplier's. Who gets stuck with any problems? The operator, in the long-run, unless the supplier gets stuck with a significant defect and resolves the problem under the contract.

In the first case, the user will be reluctant to include such new features due to future procurements and, in the second case, the supplier will vow never again to bid with any new requirements. In either case, the industry suffers. On the other hand, let's assume the supplier comes into the procurement with a new product, asking the operator to allow this new product to compete with the more comfortable products. After some hesitation and recalling UMTA policy for maximizing competition, and because the salesman is such a nice guy, the purchasing agent says "Okay." Maintenance never understands these things, so when the new product is delivered, it gets the royal treatment -- the very royal treatment, which usually means no treatment at all. Of course, the supplier never understands how a product could possibly be causing so many problems to the operator.

Again, without the commitment from both

sides, the introduction is likely to result in failure. Sometimes we refer to such a commitment from both sides as cooperation. I believe that another major area for introducing new technology in bus operations is the lack of cooperation from suppliers and operators to work toward new technology. Operators need suppliers who are willing to develop and provide new technology. Suppliers need operators who are willing to try new technology, willing to change.

The level of cooperation or commitment will depend on the level of need or desire that the new technology represents. For the supplier it may mean new markets, larger market shares, lower costs, improved profit, higher quality, expansion of facilities, an informed growth in employment, or a combination of these and other factors. To the operator, it may mean lower costs, improved reliability, increased ridership, improved driver comfort, good public relations, opportunity for special funding from government agencies, or a combination of these and other factors.

In most cases, the alternative is the security blanket of no change. The risk of introducing new technology is not to be taken lightly, but as operators wish suppliers to understand their concerns, so must operators understand the concerns of suppliers. Suppliers are often asked to design features recommended by non-suppliers who share absolutely none of the risks of such innovation. Operators are quick to point out that what works at property XYZ will not work at their property, yet often fail to understand that while feature XYZ works well on a Brand X bus, it simply won't fit on my bus.

Successful development and introduction of technology must be done in cooperation with risks shared by all the parties. The security alternative will be selected time after time.

As a manufacturer, I obviously address these concerns mainly from the supplier's viewpoint. As a salesman, however, I find that the best sell and the easiest sell is when I can offer something that the operator wants, at a price that is attractive to the operator, which usually means low-bid in this business. According to the operator's terms, which I can't stand or understand, and agree to stand by the operator through thick and thin to ensure a successful program. So I feel I am very familiar with both viewpoints. Nevertheless, I will let them express their viewpoint today.

I just mentioned terms. A very interesting word. Perhaps you know it as boilerplate. I have several other terms for it which I know go either up or down. Over the last few years, I have had the opportunity to discuss bus purchase terms with lawyers -- they prefer counselors -- for many transit systems. On several occasions, after knocking out an acceptable set of terms, I've asked the counselor to switch seats for a minute, off the record, to tell me honestly -- if you were representing M.A.N. in this procurement, would you recommend we bid to these terms and conditions? Those who can stop laughing and who are brave enough to answer, always say "No." Not a single one has ever said Yes.

What does that say? I was always taught that a good contract protects both or all parties to the contract. Do you believe that the contracts under which buses are purchased today protect suppliers as well as operators? Let me suggest that each of you review the terms of your last bus purchase from the supplier's standpoint. These terms usually apply to the home bus including any new technology which the operator is specifying. Just as I expect to give the operator special consideration for allowing my new product to be bid, can't operators share the risk of the new technology which they wish to purchase? Such cooperation has practically disappeared, but it is easy to accommodate through such means as non-mandatory options, limited warranties for the specific feature, third-party warranties with the feature supplier, negotiated change orders for the design feature after contract award, limiting the actual percentage of products with that feature in order to limit the risk, and more.

Contract terms are an unnecessary barrier to the introduction of new technology but, in most cases, this barrier is impossible to remove. Most operators assign the task of bid procurements to maintenance and, when available, to engineering personnel with official communication to the Purchasing Department. Pre-bid meetings are then held with technical and purchasing professionals who, quite understandably, have a great deal of reluctance to modify contract terms and conditions. Asking these people to address the legal subjects is no doubt different from asking a lawyer to handle the questions regarding floor covering, tire size, and rain gutter cross-sections. But just try to get in to see the lawyer, excuse me, counselor, to discuss the merits of the specific request. I am sure you understand my point.

Again, cooperation is the key to working out acceptable contract terms that protect both parties and encourage the introduction of new technology.

I'd like to address one more subject today. What role should UMTA play in the development and introduction of new technology in bus operations? I think many of us would agree that UMTA has, at times, been a barrier to the introduction of new technology. As an active member of the Bus Technology Liaison Board, funded by UMTA, I know that UMTA wants to be a catalyst, not a barrier, to new technology. UMTA has certain restraints imposed by the Congress and/or the Administration under which it must function. Appreciation of these constraints is essential to understand how three-party cooperation with operators, buyers and UMTA may effectively utilize and encourage introduction of new technology. Obviously, the federal government should not be put in the position to endorse a specific product from one supplier. Often the support of a particular feature results in just such an endorsement.

On occasions, UMTA has provided funds to private companies to develop particular products or features, especially research and development projects. This apparent inconsistency should be resolved. Government discourages private investment in research and development if it pays for the R&D of one particular supplier. This, in effect, inhibits competition and development of the new technology. Federal government should direct R&D funds to operators to develop features desired by operators in a manner that encourages competitive development of features, wherein all parties share in the risk. Active support from UMTA is necessary to provide comfort to operators and suppliers. We must make the commitment to the introduction of new technology. All new ideas, all changes, will not be good ones. But only by trying new ideas can the good ones be identified and the not-so-good ones be dropped or sent back to the drawing boards for further work. Suppliers cannot afford the full cost of both development and introduction of new technology. The operator, who must be responsible to the public it serves, cannot afford the cost of trying every single new idea that is brought forth by entrepreneurs, consultants, engineering class projects, and many, many factors. UMTA can encourage responsible introduction of new technology, offsetting the costs of the not-so-good projects, and passing the news of the more successful products. It can become a truly important and more effective partner in the development of new technology in bus operations.

But, please don't encourage more bus manufacturers to move to America. I think there is enough new technology for current bus manufacturers to go around here.

In closing, let me say that the introduction of new technology cannot succeed if the operator does not contribute and participate with the same level of commitment expected from suppliers. While all projects may not succeed, everyone gains from those that do. By cooperating together, UMTA, operators, and suppliers can begin to cross these barriers together in sharing the introduction of new technology as it will benefit the person we all serve -- the bus rider. I am sure that discussions like this will lead to that cooperation.

Thank you again for the opportunity to present my concerns. I'll take any questions.

MR. AURELIUS:

We'll have to have questions following it all if we can get any time. Here's John Wilkins.

MR. WILKINS:

Thank you, John. Some of you were at the previous session, so my comments might be a little repetitive. Let me start my discussion on barriers with what I feel to be the primary mission for any transit operator, and that's high-quality service, service quality -- whatever you want to call it. Reliable, on-time service in sufficient quantities.

New technology has not always been sensitive to that very basic and primary need of the transit operator -- wanting to go in many directions toward that, and I think we have seen lately rather significant happenings there.

There have been some significant problems lately in which the introduction of new technology really did not recognize this major need of a transit property. On the rail side, you can cite the R-46's in New York -- a very nice car, very poor availability and, when available, not very reliable. At least initially.

But the bus industry has seen new entrants, and it's seen a turnover of ownership which is almost like a new entrant. It has seen a turnover of key staff in much of the suppliers' personnel. This all has an impact on the type of product that is delivered to the transit industry, excluding whether there is any new technology put on that vehicle or not.

I think suppliers themselves have had a major stake in raising some of the barriers. I think many firms have come to the transit marketplace with insufficient funding to support their efforts. There is insufficient testing of the product that they wish to sell and when they make a sale, many times, there is insufficient support of that product. When the interest in the supplier wanes, even when he fails or decides that the transit market was not for him unless the transit industry was left with the problem to contend with. But there is no saint in the transit industry either. Where has the technology been coming from in the transit industry? It's basically been coming from outside the industry. The last time that technology came

or was guided from within the industry was probably with the PCC cars, a picture of which you saw a short time ago. Since then, the transit industry has really taken whatever was made available to it. Some properties have had sufficient resources to enter into their own R&D. UMTA has helped the effort. Many smaller systems take what they feel is available and many times they take new technologies that are beyond their capabilities to maintain and to operate.

In the turnover of suppliers, the philosophy is of building from scratch. This is seen innumerable times and in innumerable projects, maybe more so on the rail side than on the bus side.

What has been the result of all this? The result has been that you now have an industry which is basically technology-shy, at least when it comes to the rolling stock in many instances. We're buying yesterday's technology. As for the specifications -- I am sure many suppliers have said they won't buy it unless they've got a million miles of proven mileage on it. We want that reliability. So the cars that were purchased in San Diego, Calgary, and Edmonton were unsophisticated cars in a lot of systems, but very reliable cars.

What's next? How do we really try to address this barrier? I think suppliers have to come more and more to realize what our main mission is. We have to provide reliable service. We cannot use our service environment as a testing place. When we put units out there -- when we buy a hundred of this or a hundred of that, we've got to put them out in a very reliable manner. Our riders require this and the political infrastructure is very demanding in this respect. What we really need is the marriage of the suppliers of technology, the suppliers of hardware (sometimes they are different), and UMTA has acted as a catalyst in this area. All of this has to be blended with the operator.

I hope I read the slide right when the gentleman yesterday was making a presentation on the Helsinki system. If I read the slide correctly, that system was operational in 1977. It did not carry a passenger until 1982. They were using new technology. They had an AC propulsion system on those cars. It was a five-year test. Now I don't know all of the details, but they didn't carry a passenger until they felt they had the reliability that they needed to operate that system.

I guess, you know, the industry, too, has to become more involved. We have to get back to the point where we were with the PCC. Specifications have to grow out of the industry. It has happened that way in Germany as John mentioned, with the VOV buses. It happened in Switzerland with a standard trolley coach and other vehicles. The industry decides what they want and puts out specifications on the vehicle and the manufacturers responded. I think that overcomes a lot of the problems that Mr. Pickett discussed in his presentation, but again, it is incumbent upon the transit industry also.

That's my very short synopsis of the barriers and I think you can't point a finger at any one person but we all have a piece of the action. Thank you.

MIKE BUCKEL:

Unlike some of the other speakers, I'm going to take the opposing viewpoint that there are virtually no barriers to new transit technology. In the past decade, I was party to some 41 technologies or products, whatever you want to call them, in one way or another. And they fall into a number of categories.

In the complete vehicle design, we have seen innovative body construction in the 2 ADBs, the introduction of articulated buses, an experiment with double-deck buses, the low floor experiment, and, of course, all new ADBs with a number of features. In the power plant and drive line area, you can include air starters, T-drives, V730, turbo-charged engines, gas turbine engines, fuel cells, electronic transmission controls, stored hydraulic energy propulsion, independent front suspension, radial tires, fuel additives, low tire sensors, and non-standard diesel engines and transmissions, non-standard meaning something other than what has been around for the last 30 or 40 years.

In the body components, we have seen plastic windows, electronic destination signs, energy absorbing bumpers, roof ventilators, cantilevered seats, energy-absorbing seat construction, stop-requested signs, reintroduction of step-treadle doors, emergency escape provisions in the windows, the braking area with retarders both electronic and electric and hydraulic, the dual air-brake system, automatic slack adjusters and anti-skid brake systems.

Others were wheel-chair lifts, rotary screw compressors, alternative fuels, specifically methanol, automatic vehicle monitoring systems, and off-board electronic condition diagnostics such as is being tested in New York City.

Specifically in the trolley coach area, there have been solid-state controls, power regeneration on those solid-state controls, AC drives, auxiliary power units, and a flywheel energy system.

Where did all of these technologies come from? Well, they came from a lot of places -- certainly the government regulated some of them, such as the dual air-brake system. The bus manufacturer offered some of these innovations -- the ADBs, T-drives. Suppliers to the bus manufacturers offered things like the V730 transmission, M.A.N. engines, RENK transmissions. There were joint industry-government projects that evaluated some of these technologies. The articulated bus is a notable success. The low floor and the gas turbine proved to be unsuccessful but they were properly evaluated before they entered revenue service. The operators generated some of the technology -- the air starters, retarders, radial tires. And there was some local political pressure that required such things as lifts and certain fuel additives that may or may not have been beneficial.

The 41 technologies identified can be categorized in the following way. These are a partial listing of the technologies, but they are good examples of some of those things. Certainly the retarders, articulated buses, and energy-absorbing bumpers were overwhelming successes. You see very little criticism of any of those in any part of the country. Plastic windows, cantilevered seats, T-drives are very successful and some amplifications, but they are not the things that are needed in everybody's application.

Some of the technologies are certainly introduced prematurely and developed in revenue service. These are the V730 transmissions, the advanced design bus, electronic destination signs, which are just three examples. Others were not introduced because they were evaluated in a non-revenue environment and never saw transit service on a regular basis.

Of the mandated technologies, turbo-charged engines were a result of the emissions regulations. The anti-skid brake was a specific regulation as were lifts. And there is still a lot of technology under evaluation. Methanol fuel, fuel cells, and stored hydraulic energy propulsion systems are just three.

What do you do with all these technologies and how do you control them? Well, with ten (10) manufacturers now in the market, competing for some three thousand (3,000) buses, there is going to be a lot of new technology introduced. Everybody is going to have to have something better than somebody else. What does the operator do with all of these new things that come along? Well, certainly you can't have a specification and have 10 bidders. Otherwise, you would never manage it. You would never know what you'd get. There'd be no standardization at all. The operator is responsible for deciding what equipment he needs, what he wants, and that's by test in his own environment to qualify the kind of products that he would be willing to accept in a new bus purchase. And he must specify those products that he is comfortable with, not necessarily that the manufacturer is comfortable with, and limit his bidding process to just those manufacturers who supply the kind of technologies and innovations that an operator can live with. Thank you.

ARTHUR SCHWARTZ:

Since we are running out of time, I am going to make my remarks very brief. I am going to discuss what I consider one of the major barriers to technolgy and that's the technology itself that has been offered. I think much of what we have seen has been offered without too much thought as to what the real needs of the operators are.

One that has already been emphasized, of course, is reliability. The other is, particularly in these days of decreased support in transit, reducing costs. We've talked a lot in this program about reducing energy costs. However, energy costs, as Mr. Wilkins pointed out in his system -- and it's about the same nationally -- account for only seven percent of the total cost of the system. Seventy-three percent of the costs of the system are labor, based on the most recent national average.

What have our innovations done to reduce labor costs? About the only thing that I can think of off-hand in the bus area is articulated buses which, where they have been entered, are quite successful. On the rail side, we have spent a lot of money on automatic train operation, automatic fare collection -- none of which seem to have made a very great dent in labor costs. And possibly, for example, on automatic fare collection we have applied new systems. Three of the five still have full-time attendants at all their stations. My congratulations to the two that don't.

Instead of directing technology to important issues, I think we have directed a lot of our technology to peripheral issues. The low-floor bus was a very good example. I think there was a lot of effort spent on a low-floor bus, after it was obvious that a low-floor bus would end up costing more than it was ever worth. Again, some of the best examples are from the rail side and what I call the advanced technology side, the new systems side. For example, we've been hearing for years about the elevated system that is going to be so small and inconspicuous to put up and will replace all this expensive subway construction. Well, boys, it isn't going to happen. That structure wouldn't hold itself up, let alone any vehicle, no matter how light it looks.

If you don't believe me, look at a 40-ton axle-loading railroad bridge and a 10-ton axle-loading highway bridge. They don't look that different.

Another one of these issues is the vehicles that will run two seconds apart -- the very close headway systems that keep coming back to us. That's another one that isn't going to happen. Very simply, a system's headways are controlled by the need to stop a vehicle safely. I'm thinking of a vehicle where the passengers can be standing, walking, or are otherwise unrestrained. The proponents of close headway are always indicating that a vehicle doesn't stop instantaneously. Well, it does if the bridge is knocked down.

I could go on with several more examples like that but we are very close to running out of time, so I just want to say that in all the development of new technology, think it through first, think through what it is that is going to be accomplished, and what is the goal of the technology -- is it worthwhile? -- before you spend a lot of effort on developing it.

And I think one of the reasons for this emphasis on technology for its own sake, rather than technology for the sake of user needs has been just what Mr. Wilkins stated -- it has not been an industry-driven thing. Technology has been a supplier-driven technology. With that, I am going to close.

MR. DIGGS:

Thank you, John. We are running out of time, so I will also be as short as I can. The subject of new technology is in some way distressing to the transit maintenance superintendent. If somebody is asked to test that new technology before it's ever going to become available on a large basis, there are some barriers to testing which I think everyone has to realize are there.

Experimental or prototype equipment which is supplied as new technology sometimes has the connotation of being ready to work and people that are outside the industry, and unfortunately, sometimes inside the industry, don't realize that this is experimental or prototype. We, in the maintenance department have to justify a lot of extra time to perfect the equipment which, even though it has been designed and tested, is going to be put out on the road and there are going to be a lot of strange things that are going to happen. We have to justify the time to perfect it and keep it on the road. We have to find time to experiment with fixing it because there is no service manual written for most of the new technology items that we are asked to test. We have to machine or make parts because you just can't buy them.

The other barrier that sometimes comes up is people. Drivers, mechanics, cleaners, dispatchers all have a resistance to change and their attitudes have to be changed. The management team has to work with these people and spend a lot of time getting them turned around to have a commitment to getting this technology on the road.

The other problem we have is time. We have to have a willingness to devote the time to training and familiarization within the mechanics, for instance -- the mechanics don't like change because they don't like to have to think too much about what they're doing. They don't want to stop and go to the book. They don't want to do all of these new things. There are new diagnostic tools which a lot of the mechanics have never even thought of -- a computer to diagnose what's wrong with their bus. We have to take the time to train them to use this new equipment. We've got to train them to use the new tools that have come out.

Another thing that could be a barrier is the manufacturer's support. We need people on the manufacturing side who are interested and committed to the development. The R&D must continue even though the product has been kicked out the door. If the R&D doesn't continue, it's probably going to be a failure.

Another thing we need some help with is project management and it is a barrier to the introduction of new technology, believe me, if you don't have a consultant team with their feet firmly planted on the ground. The one thing that will kill a project faster than anything else, in my opinion as a maintenance superintendent, is a consultant who comes in with his head in the clouds, a pie-in-the-sky attitude, doesn't have the slightest idea of what it is like to operate a bus system. The consultant has to be committed. He has to have ample resources to carry out all of the unexpected tasks that might happen, and he has to react to variations in what he plans or in what the sponsoring agency plans. There are going to be a lot of changes in what was written and in what actually happens when that new technology goes out on the road. A new bus has differences in drivability. The computer on the new bus has only been in service six months and it fails. There could be a lot of hours spent by this consultant because he is the one who is probably going to be most informed about this new technology, in diagnosing these problems.

Another problem we have is money. The funding agency must be found. The politics must be handled. There are a lot of Boards of Directors who are very reluctant to commit their transit system as a test bed because they know it's going to cost them money in the end.

You need a host property that is committed and interested. An agency has to, for some reason, have something in it for them -- has to be committed to demonstrating the new technology. Maybe it's ecology, maybe it's conservation, maybe it's better service. There could be a lot of reasons, but if you don't have it, that's another barrier.

You need support from associated industries. Not just the manufacturer of the new technology, but everything that the piece of technology touches. You need support from a lot of different people -- not only the engine manufacturers, you need the coach manufacturers, you need the fuel people, you need the oil people -- all of the other agencies and other manufacturers.

Another barrier is people not being linked to expect the unexpected, and being able to react to it. You should solicit ideas from everyone on your staff when you're introducing new technology, and be willing to get everyone involved; otherwise, you are going to have a barrier that you cannot overcome.

And I guess probably my final point is very brief -- the government people should not mandate technology. You cannot mandate technology. There have been too many examples of that happening in the past five or ten years. It's cost us a lot of money. It's cost us a lot of time. And I think when the new technology is mandated and it hasn't been developed and tested yet, I think it hurts, overall, the introduction of new technology.

Thank you.

MR. AURELIUS:

Wayne's remarks about mechanics being unwilling to do something different triggered a memory that might be a good closing point. When I arrived in Seattle, the decision had already been made and articulated buses were to be investigated, and if the investigation proved successful they were to be purchased. Five years later, the first articulated bus arrived on the property from the production series. And it came into a new garage that we had in the Bellevue area, sometime during the afternoon. The first thing I did when I went home at five o'clock was to get in my car, and go over to Bellevue to see this bus, as I had worked so long on it. And, of course, the drivers were coming in off the runs around this time, by this point, 6:00 or 6:30. And all these younger drivers, most of whom hadn't even worked on the property when we had done our original demonstration were coming to see what this strange object was, parked over in one corner of the yard.

And they'd come in and they'd look at the thing and they'd say, "Well, you'd never get me behind the wheel of this thing;" or "Gee, I don't know how you'd ever get that thing through traffic," and similar negative comments. And then up drove one of the district company cars with a supervisor, a grizzled old guy, probably pushing sixty and he parked the car and came and looked at the bus, and he said, "By damn, if I was sure I could get one of these things, I think I'd go back on the road."

Technology, innovation, change -- it isn't everybody's bag but there are some people who want to do it and maybe those are the people who get it done.

We're just about right on time, without any questions, unfortunately. My suggestion is that I call this session formally closed, but I'd like to request that the Panel stay in place or at least be available for the next five or ten minutes, if anyone wants to stay.

QUESTION:

George, would you be willing to draw up a contract that you think would cover everything one would want to have covered, and work with UMTA on approval of that language so as to commit this specification on buses? Would UMTA be willing to discuss the shorter, revised, simpler form of contract for bus transit? Could you make a few comments with respect to that? I can remember two or three years ago, calling on Denny Howard, President of Gillig. Denny told me that, when he was head of marketing for Peterbilt Trucks from the Northwest, everything that needed to be said on the sale of a Peterbilt Truck was on two sides of a single sheet of paper. I said, "Denny, would it be possible for you guys at Gillig to do bus business [I hope I'm quoting Denny correctly] with UMTA and all the transit authorities with language on two sides of a single sheet of paper?" He said, "Absolutely. No question about it." Might this be possible, George? Not necessarily that it be on two sides of one sheet of paper, but it might be possible there could be a contract that would be shorter and more specific? Would UMTA be willing to do it, and if the answer to all of that is no, what would be wrong with having a project whereby we bid an order of buses on two sides of a sheet of paper and had a grant to cover the losses of whatever was permanent? What would happen if we did do a bus frame in such a manner? Thank you very much.

ANSWER:

Thank you. George?

GEORGE:

A brief answer. Initially I want to say, "Yes, that's a wonderful idea." I do think there are areas that can be worked on with UMTA. My fear is that we may come up with what we have today -- another piece of paper with another set of terms, that becomes inflexible to the particular needs of a particular procurement. There has to be give-and-take and, I think it can be had, but you ask the purchasing manager and the maintenance manager about liability involved and they get very nervous. You need to be able to talk with the attorneys on this. UMTA could be a part of it as well. Yes, I think a lot of work can be done on improving the terms that we do business with.

ANSWER:

Certainly the procurement document is a work document to technology introduction. Certainly we would support the understanding and the communication of alternatives to a good model contract. You've got to put it in the plural, not the singular. We will not issue a white book specification, but we would certainly be happy to work with the supplier and the operators to develop some model language that would be similar and more appropriate to the business at hand. We would suggest that, certainly, and communicate that to individual procurement agents. It is very clear. I want to make it clear, in general. We have very, very little in the way of procurement requirements at this point. We have implemented a deregulation of our procurement process and you will find that the lawyers in the regional offices are very permissive in terms of procurement documentation.

QUESTION:

May I add to this? I think what you're seeing is probably the reason that most of the variations are not among most state and local requirements. I know in dealing, for example, with this state, that everything looks as if it was written with one eye toward the State Penitentiary down the creek.

MR. AURELIUS:

Well, first off, Art stole my thunder because that's similar to what I was going to say, but I'd like to add that indeed, the transit authorities generally are public bodies -- they are usually under some form of state charter, although I suspect a city charter would be little different. Both at Metro-Seattle, where I worked before, and here at my present employment in New Jersey, state law was a very governing thing with state contract law, and it was basically written for building highways, so we said we would take what the lawyers say about building highways and apply it directly to the purchase of rolling stock. I recall in New Jersey the very first contract I saw. In fact, it was before I was even hired. When I came for my interview, I spent a day sort of sitting in on a round-table on procurement of locomotives, and they had a specification that was like building a sewer line or a highway, where the state inspectors have the right to be in the GMC or GE locomotive plant and if they didn't like something, they had the right to say, "Everybody out of the ditch!" Now, we don't have the right to say, "Everybody out of the ditch" in a bus plant or in a locomotive plant. That supplier is only responsible for delivering something. He is not responsible for setting up a production line that meets the whims of an inspector. But we're bound by the state laws to get any of that stuff changed -- we're up against a whole row of state attorneys or other attorneys who are charged with keeping you out of trouble. The way you keep out of trouble is to obey the law. It's very difficult and I don't know the answer to it.

QUESTION:

And in the private days, you used to buy jimmies, I believe, by filling out their sales form.

ANSWER:

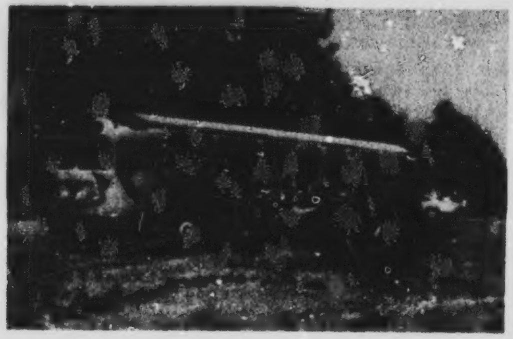
So, yes, you can sell buses that way, but the question is, can you buy buses that way?

MR. AURELIUS:

Is there anyone else who wants to pose a question? Meeting adjourned. Thank you very much.

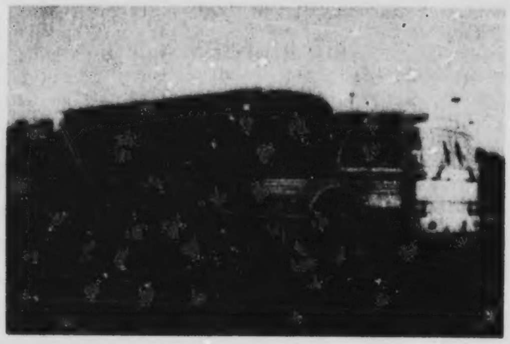
INTRODUCTION, John Aurelius Sample Slides

GG-1 LOCOMOTIVE (ca. 1935) - A large fleet of these electric locomotives was built by the Pennsylvania Railroad for the newly electrified lines from New York to Harrisburg and Washington. Top speed was over 100 MPH.



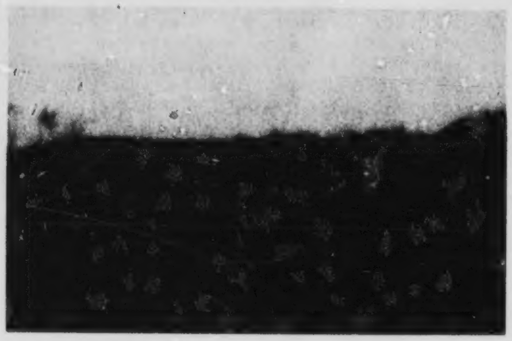
DIESEL TRANSIT BUS (ca. 1955) - The diesel engine, automatic transmission and large body size made buses capable of virtually supplanting the streetcar and trolleybus. This example, by General Motors, is 40 feet long and has air suspension.

HIGHWAY COACH (ca. 1935) - With the growth of paved roads across the nation, long distance bus travel became practical. The Greyhound Company created a unified service out of many small operators.



SCENICRUISER (ca. 1955) - This highway coach by General Motors was 40 feet long, diesel powered and had air suspension and air conditioning. The 1-1/2 deck construction provided better viewing for passengers and a large belly for luggage and packages.

PCC STREETCAR (made from 1936 to 1952) - The PCC car was a standard design developed as a cooperative effort of the electric railway companies. Any carbuilder could produce the PCC car under license. Pullman-Standard and St. Louis Car Co. built them in the U.S.



TRANSIT EXPRESSWAY (1964) - Built by Westinghouse under an UMTA grant, this test track in Pittsburgh was a prototype for a fully automated, driverless rapid transit system. The rapid transit line was never built, but Westinghouse has installed several successful systems in airports and theme parks.

BART, THE "SUBWAY BEAUTIFUL" (1972) - Serving San Francisco and its suburbs in the East Bay, BART was built to a high standard with many innovations. Several new subways have been built since BART and most of them have adopted some of its features.

"NEW LOOK" TRANSIT BUS (built 1959-1976) - General Motors produced a large number of these buses and they became a standard throughout the U.S. and Canada. They were available both in transit and suburban configurations.

"STANDARD" LIGHT RAIL VEHICLE (ca. 1976) - This design was intended by UMTA to replace the PCC as the standard light rail car. Only one production run was made, by Boeing-Vertol for Boston and San Francisco. Several light rail car orders have been built since then, of different designs.

MODERN INTERURBAN LINE (ca. 1978) - The "Tijuana Trolley" runs from San Diego to San Ysidro, CA across the border from Tijuana, in Mexico. The line was built quite cheaply, using a former freight railroad and an off-the-shelf German car by Duewag. A conscious effort was made to keep the design simple.

ARTICULATED BUS (1981) - This 60 foot transit bus was built by Ikarus (Hungary) and Crown Coach. The joint between the second and third axles is fully enclosed by a bellows, and passengers can cross between front and rear units at any time. Buses of this type are offered by Ikarus, M.A.N., Volvo, Neoplan and Scania in the U.S.

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Innovative Propulsion Systems

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INDUCTIVELY COUPLED POWER SYSTEMS FOR TRANSIT — AN OVERVIEW

J. G. Bolger
Inductran Corporation
USA

ABSTRACT

The technology of inductively coupling power to electric vehicles has now been advanced sufficiently that it should be considered for use in certain new transit systems.

The incentives to deploy inductively coupled power systems (ICPS) instead of diesel, trolley or third rail systems include freedom from wear, visual clutter, exhaust emissions and noise, and operational flexibility. The strongest incentives will become the communication and control capabilities between road and vehicle that are established by the magnetic link that is established by an ICPS.

The unique characteristics of the ICPS should be carefully considered in evaluating its potential in a particular application. Among those of major significance are electromagnetic effects from the system, power transfer limits, and tolerance requirements on guidance and airgap.

The capabilities of the magnetic link in providing communication and control to vehicles makes a new generation of automatically controlled transportation system possible.

BACKGROUND

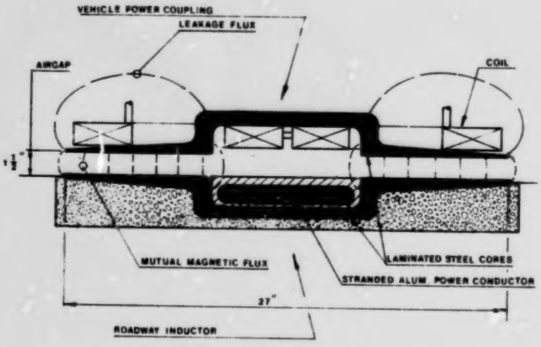
Power systems being used for transit were selected in large measure to suit the characteristics of particular routes and the power requirements of the system's vehicles. Inductively coupled power systems (ICPS) will find their place in the ground transportation industry not so much because of power system characteristics as because of the foundation that they create for fundamentally new transportation modes. ICPS would have difficulty in competing closely with trolley and diesel systems in terms of cost when mapped on today's elderly transit technologies, although its freedom from wear, visual clutter, noise and emissions, and operational flexibility provides other incentives to deploy them. In highway applications those incentives to implement ICPS are powerful, and their operating cost advantages are great.

The first of a new generation of transit modes employing ICPS is in its engineering prototype state of development. This development incorporates many of the unique new capabilities of a magnetic link between road and vehicle. The goal of these modes is high capacity, convenient transportation systems that can be profitably implemented by the private sector without subsidies.

Characteristics and capabilities of magnetically linked transportation systems that are significant to the achievement of the goal are reviewed below.

POWER SYSTEM CHARACTERISTICS

Figure 1 is a cross section of an inductive power coupling. Constant current, typically several hundred amperes at a frequency of about 180 hz flows in the power conductor. The current causes magnetic flux to circulate thru the steel cores of the inductor and power coupling, inducing voltage in each of the conductors around which it circulates. The induced voltage can be increased up to a condition of resonance by adding exciting ampere turns in the coupling or decreasing the airgap.

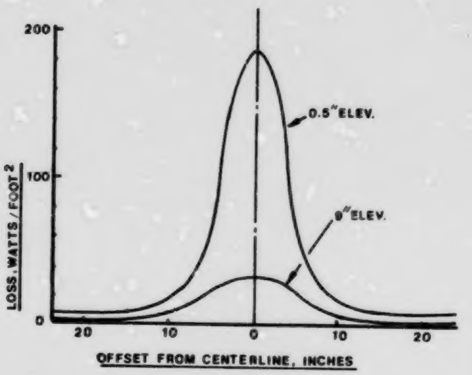


POWER SYSTEM CROSS SECTION

FIGURE 1

The maximum load rating of a coupling is the product of voltage output in terms of volts per turn, and the inductor current. The constant current in the power conductor is accommodated in an appropriate conductor cross sectional area. The voltage relates to a certain amount of circulating magnetic flux that requires a particular cross sectional area of laminated core steel. Thus the power rating of the inductor is reflected in the amount of materials used in its construction.

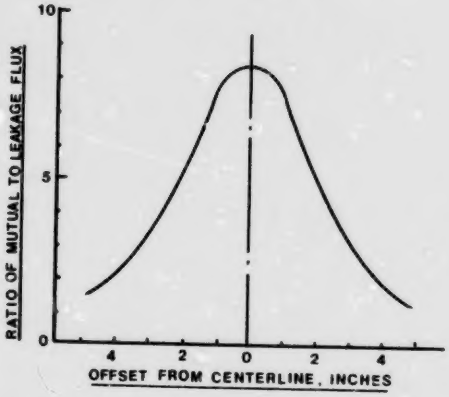
The alternating magnetic flux near the inductor will induce voltage in any conductive material around or thru which it passes. The currents resulting from these voltages cause parasitic power losses and can interfere with the operation of sensitive electronic devices. The electromagnetic (EM) effects are exponentially related to the amount of current and frequency in the inductor. Figure 2 illustrates the magnitude and distribution of parasitic loss in a steel sheet above an inductor. The figure shows that the loss is maximum in a narrow stripe above the center of the inductor, and that the loss increases rapidly with closeness to the inductor.



POWER LOSS IN A STEEL SHEET ABOVE AN INDUCTOR VS. OFFSET

FIGURE 2

The EM effects from an inductor stringently limit the power density, i.e., the power rating per unit of coupled length, that should be used in a particular environment. On a city street the proximity of pedestrians who might depend on pacemakers, the presence of pipes and conduit under the street, and the probability of dense slow moving streams of non-ICPS vehicles above the inductor encourage the use of reduced power densities. Higher power densities will be feasible on freeways and exclusive rights of way. An inductive coupling such as shown in Figure 1 can operate adequately with the airgap clearances shown and with about 4 inches of misalignment. A favorable ratio between the linking 'mutual' magnetic flux in the coupling and 'leakage' magnetic flux must be maintained for the coupling to perform adequately. Figure 3 shows how this ratio degrades as misalignment of the coupling increases; a similar effect results as airgap increases. In order to increase either the working airgap or the tolerance for misalignment, while maintaining an adequate ratio of mutual to leakage flux, it is necessary to proportionally increase the size of the inductor and coupling.



RATIO OF MUTUAL TO LEAKAGE FLUX VS. OFFSET

FIGURE 3

Magnetic forces on an automotive coupling are on the order of hundred pounds, and a small centering force occurs when the coupling is misaligned. If power density is increased by increasing the coupled voltage, these forces increase rapidly.

Changes in airgap, alignment, and load have a substantial effect on voltage ouput. It is essential to provide a means of maintaining a stable voltage ouput in the face of these continuously changing parameters. Inductran Corporation's proprietary methods of accomplishing this include mechanically controlling the coupling's airgap, or providing an electronic control system that operates without varying the airgap.

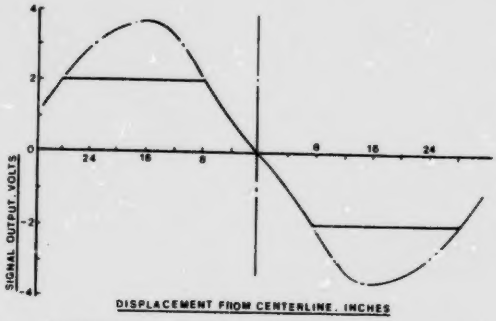
VEHICLE CONTROL CAPABILITIES

The magnetic link is a versatile tool that can provide reliable sensory inputs to several important control subsystems. Inductive devices are now being used for vehicle detection, and speed control, in some transit systems. These functions can be incorporated in magnetically linked systems as straightforward overlays on the basic power system as generally described below.

Wayside Vehicle Presence Detection -Sensing windings on the cores of the power inductor can provide high level detection signals. The construction of the inductor is such that the sensing can be economically accomplished in such short lengths that high resolution detection is available with a considerable degree of redundant protection against single point failures.

Wayside Vehicle Velocity Detection - The velocity of vehicles can be reliably monitored from the wayside simply by measuring the incremental time between vehicle detections at successive vehicle sensors.

On Board Vehicle Guidance - Figure 4 shows the output characteristic of a guidance sensor of a design that we have developed. It can be seen that the sensor has a broad lateral range. The signal output level is an easily adjustable parameter, and the signal vs. displacement gain near the centered position also can be tailored to suit particular steering servo systems and desired tracking accuracy.



GUIDANCE SENSOR OUTPUT VS DISPLACEMENT

FIGURE 4

Roadway-Vehicle Communication - A communication link can be incorporated in the inductor that permits data transfer at KHz rates in spite of the fact that the inductor's design is specific to frequencies more than an order of magnitude lower. This link will be used to transmit speed codes to vehicles and will be available for vehicle identification and subsystem status reporting.

PROJECTED MAGNETICALLY LINKED SYSTEMS

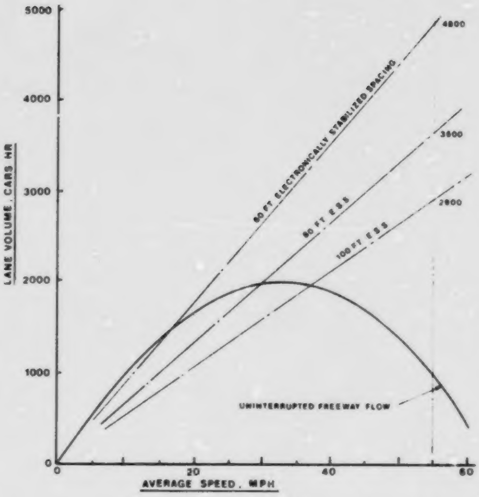
The general shape of future well designed magnetically linked systems can be discerned from the above review of characteristics of system components and capabilities.

An overriding consideration in these systems will be to minimize their power density because of its adverse effect on EM effects, capital cost, and magnetic forces. This consideration in turn makes it critically important to utilize vehicles with low energy consumption. Light vehicle weight with efficient regenerative propulsion systems are indicated. Minimum use of stored (battery) energy is also indicated because of the weight and inefficiency of batteries.

In the case of systems for use on roads with irregular surfaces such as city streets, the relatively small airgap clearances in couplings encourages the design of vehicles with short wheelbases, while power density constraints indicate the use of the maximum power coupling length that can be fitted to the particular vehicle.

The tolerance for lateral misalignment in power couplings is only a few inches either side of centerline. This relationship is highly disfavorable to a vehicle that must maneuver around the random obstructions that occur in street traffic. The time that is spent with the vehicle misaligned requires either a compensating increase in power density, or the provision of a lateral servo positioner on the vehicle to center the coupling.

The diverse control and monitoring capabilities that accompany the use of the magnetic link are of great significance to the performance, safety, and operating cost of a transportation system. Figure 5 illustrates the potential of automated headway control in an existing system--in this case the freeway-automobile system. The characteristic traffic volume vs. speed relationship is shown to peak at about 2000 vehicles per hour per lane at less than 35 miles per hour with vehicle spacing averaging about a hundred feet. With headway stabilized at 80 feet, the lane would be capable of safely sustaining a flow of 3600 vehicles per hour at 55 miles per hour--an increase of 80% that would save tens of thousands of man hours per year and break the worsening cycle of traffic jams. Even higher percentage increases are possible in transit systems when the steel wheel-steel rail adhesion limit is removed by using magnetically guided, rubber-tired equipment so that full advantage can be taken of closer headways at high speeds.



FREEWAY LANE TRAFFIC VOLUME VS. AVERAGE SPEED

FIGURE 5

There have been no ground transportation system innovations since the advent of the electric steel railway and the automobile that were of a scope to have a major effect on the nation's transportation capacity, although the motor bus and advanced rapid rail systems provide critically needed local services. Magnetically linked, automatically controlled transportation systems offer the prospect of new highway and transit modes that can preserve and expand the nation's mobility, and return the transit industry to the status of unsubsidized economic viability.

HIGH SPEED MAGLEV TRAIN

Thomas B. McDonough
The Budd Company Technical Center
USA

Summary

The MagLev Train is an ultra-high speed transportation system in which vehicles are magnetically levitated, guided and propelled by synchronous linear induction along an elevated guideway at speeds up to 200MPH.

The paper will include a description of the MagLev Train system, the principles of operation, the state of the development and the 250MPH test and demonstration site and the results of two studies of potential intercity aplications.

In the world today, there are a number of modern, high speed ground transportation systems. Two notable systems which are operating in revenue service are the Japanese Shinkansen and the French TGV, both which operate in the range of 150-160MPH. In addition, there are a number of other systems under development to achieve these same goals, e. g. the British Advanced Passenger Train. The best we have in this country is the Metroliner which, until recently on the northeast corridor between Washington and Boston, was operating in the range of 120-130MPH, even though it was designed and demonstrated to operate at 160MPH during the 1960's. The reasons why the United States has fallen behind other developed countries of the world in providing high speed passenger service appears to be a lack of national commitment.

But our interest is awakening. There are a number of corridors in the United States currently studying new high speed passenger ground transportation systems. Certainly, these modern high speed wheel on rail systems should be evaluated for these applications. But I would like to tell you about an even higher speed system, one that does not ride on wheels - a train that flies - at 250MPH. This vehicle is levitated above its guideway by magnetic forces and propelled at super speed by electromagnetic forces. Besides its greater speed, MagLev has other characteristics which make it attractive. It rides on air with no moving parts and, hence, is friction free.

There are two significant developments under way in the world today, and these are off shore and have enjoyed the support of their respective governments. One is German and one is Japanese.

In Germany, during the early 1970's, experimental vehicles were developed and tested by MBB, Kraus Maffei and Thyssen Henschel. During this period, the MBB Comet achieved a speed of 400KPH, or about 250MPH. Then, with government motivation, the German industries joined forces to develop the TR04, a vehicle which carried 20 passengers and achieved a speed of 150MPH. Next came the TR05, the first revenue use of MagLev. This system was operated during 1979 at the Hamburg Trade Fair. The vehicle carried 75 passengers at 50MPH for a distance of approximately one mile. During the fair, the service proved reliable and safe and transported 75,000 passengers.

Now let us consider the developments in Japan, those of the Japanese National Railway. In the 70's, the ML500, an unmanned test vehicle, achieved a speed over 500KPH or 300MPH. The inverted T-shaped guideway permits no room for passengers. The guideway was reconfigured into a "U" shape in 1980 and a new vehicle, the MLU-001, was tested for the first time in November of 1980. More recently, a manned three-car train was tested. The middle car carried passengers.

The next logical step is the development of a full scale vehicle and test track to demonstrate the performance, safety and endurance of the system. Only the Germans have taken this step. Consequently, the German development is at least five years ahead. The German system is the Transrapid 06. It is capable of 400KPH or 250MPH operating speed and carries 100 passengers per section. The test track is 20 miles long and is located in northwest Germany at Emsland. The prototype vehicle has been built and testing has begun, but before I discuss the Emsland project further, let me review how MagLev works.

Recall that MagLev is both levitated and propelled by electro-magnetic forces. The levitation and lateral guidance magnets are located on the vehicle which wraps around and underneath the fixed guideway. The magnets attract reaction rails which are fixed to the guideway. The result is that the vehicle is lifted and centered on the guideway by attractive magnetic forces. This is the reason the German system is called an attractive system.

The vehicle is propelled by a linear motor. The linear motor operates similarly to a rotating motor, with which we are all familiar, except that the motor elements are unwrapped and laid in a flattened or linear arrangement. The motor stator, a three-phase winding, is mounted on the underside of the guideway. The equivalent of the rotor in the rotating machine are the levitating magnets, which are mounted on the vehicle structure. These react with the three phase electromagnetic fields created by the stator windings to propel the vehicle forward.

The vehicle has a substantial undercarriage which functions similar to rail car trucks. The vehicle itself is supported on an air bag suspension, which assures a comfortable ride. Now I will return to the Emsland project.

The full scale two section vehicle has been fabricated and is under test currently at Emsland. The test track has a dogbone plan form with loops at the northern and southern ends. The track length is 20 miles, but the length of a round trip is 30 miles. It is located at Emsland in Northwest Germany, near the Dutch border. The construction is well under way with a construction of the southern loop scheduled last. Power conditioning equipment, switch assemblies which utilize a motor driven flexible steel beam, and the maintenance facilities are all in place. In addition, there is specialized equipment for guideway and vehicle maintenance and construction.

A single section of MagLev is 90' long, 12' wide, carries 100 passengers and, fully loaded, weighs 125,000 pounds. Sections can be coupled to form trains, with a minimum of two sections. The test train is a two-section train, which will achieve the speed of 300KPH or 190MPH by late fall and a speed of 400KPH or 250MPH during 1985. The Emsland project will be opened formally in September of this year

I described the new super speed ground transportation system available for the transport of passengers. But the fact that it offers super speed ground transportation or that it is a new technology is not enough to insure its implementation in the United States today. Within current economic and political environments, the implementation of a new ground transportation system is dependent critically upon its financial viability. There are a number of characteristics of MagLev which enhance its economics. One, of course, is its super speed. Another is the low maintenance associated with the lack of moving parts. Still another is its superior grade climbing ability. Maglev can climb grades up to 10% while a wheel on rail system, which is limited to adhesion, can climb only 3-3½% grades. I can best illustrate by example. Let me review the results of a study we performed for a new ground transportation system between the cities of Las Vegas, Nevada and Los Angeles, California.

We developed routes for the modern high speed rail systems and the super speed MagLev systems. These routes include the use of existing rail, power line, and highway rights of way. There are two mountain ranges between Los Angeles and Las Vegas, the San Bernadino mountains near Los Angeles and the Clark mountains near Las Vegas. Both the high speed rail systems and MagLev routes are run through El Cajon Pass to cross the San Bernadino mountains but only the MagLev route runs through the mountain pass of the Clark mountains, which has a 6% grade. The high speed rail route must circle the mountain range, which adds about 25 miles to the route length. The superior grade climbing ability of the MagLev gives us an unanticipated advantage. The shorter route gives a savings in construction costs, and shortens the travel time. The super speed of the MagLev results in an estimated trip time of just over one hour while the best rail system is estimated to take over two hours. The faster trip time also has economic implications. Our demand study estimates that the faster MagLev would attract more than twice as many paying passengers as the best rail system, which results in more than twice the annual revenue. The capital, operating and maintenance costs were estimated for both the high speed rail systems and MagLev. These cost estimates are very close. On comparing cost estimates with revenue estimates, it is concluded that only the MagLev system will attract enough revenue to make it financially viable.

Now let me summarize. There are a number of high speed wheel on rail ground transportation systems, either operating or under development currently. Most of these are off shore and have been developed with the support of their respective governments. These include the French TGV and the Japanese Shinkansen. In addition, there are countries developing MagLev systems for revenue service, Germany and Japan. The MagLev vehicle is levitated by magnetic forces and propelled by electromagnetic forces. The German development is at least five years ahead. Testing of a full scale revenue system has begun in Emsland in northwest Germany and will demonstrate 400KPH or 250MPH speeds during 1985. Some advantages of MagLev are its super speed, low maintenance and superior grade climbing ability. These characteristics can be translated into economic advantages, even making the difference between financial viability or not. Such is the case for Las Vegas to Los Angeles.

INTEGRATED MAGNETIC PROPULSION AND SUSPENSION — STATUS REPORT

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Automated Transportation Systems
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USA

SUMMARY

The Integrated Magnetic Propulsion and Suspension (IMPS) system concept utilizes a single sided linear induction motor for levitation, propulsion, braking, guidance and suspension. The elimination of moving parts produces the potential to substantially increase reliability and maintainability while reducing operating costs. The elimination of vehicle to roadway contact produces quiet, comfortable rides.

Critical components of this system are being developed at the present time. The development is concentrated in the areas of Linear Induction Motors (LIMs), Power Conditioning Units (PCUs or inverters), and feedback control systems. A test program is underway to evaluate these components as a propulsion/suspension subsystem. The test program is limited to hover and low speed operation due to track length. Initial test results are presented.

This paper also reviews prior developments in LIMs, PCUs and control systems that led to the present configuration. The development work described in this paper is being performed under DOT/UMTA contract DTUM60-80-C-71009.

INTRODUCTION

The purpose for this project is to develop an IMPS option for Automated Guideway Transit (AGT) systems which appears to offer significant advantages compared to conventional technologies. The expected advantages are reduced O&M costs, quieter operation and improved ride comfort. The objectives of this project are to:

1. Establish the viability of the IMPS concept as a propulsion and suspension subsystem for an urban AGT system.
2. Perform analysis and component testing required to define the critical parameters of IMPS systems.
3. Verify the performance of the design by constructing and testing full scale hardware. Budgetary constraints restrict the hardware to mass simulators and low speed operation.

IMPS CONCEPT

The Integrated Magnetic Propulsion and Suspension System uses single sided linear induction motors (LIMs) to achieve levitation (Suspension), propulsion, braking and guidance without guideway contact. By combining all of these functions into a single magnetic structure, simple, lighter weight vehicles can be achieved.

The IMPS system uses magnetic attraction forces to achieve levitation. Magnetic attraction is inherently unstable and requires a closed loop control system to regulate the magnetic field to a level that produces an attraction force equal to the vehicle's weight and dynamic forces. The magnetic forces are non-linear and in addition the LIM impedance is dependent upon frequency and air gap. To regulate the magnetic forces effectively, the control system must linearize the loop gain and compensate for the variable motor impedance. These functions are implemented by a single chip microcomputer with conventional interfacing components.

Figure 1 shows the forces produced by the LIM. The thrust force is a function of the slip frequency and of the lift force. For a given slip frequency, thrust increases as lift force increases such that a constant acceleration is maintained. The lateral force is a function of displacement and has a return to center characteristic.

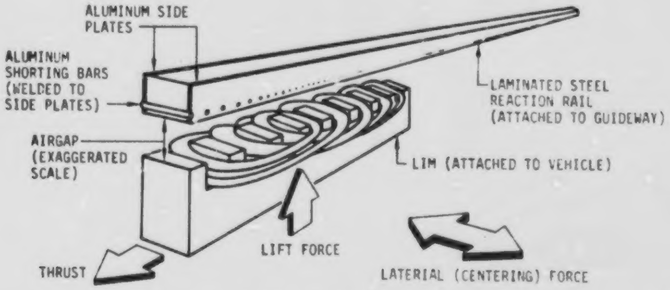
ALUMINUM SIDE PLATES
ALUMINUM SHORTING BARS (WELDED TO SIDE PLATES)
AIRGAP (EXAGGERATED SCALE)
LAMINATED STEEL REACTION RAIL (ATTACHED TO GUIDEWAY)
LIM (ATTACHED TO VEHICLE)
LIFT FORCE
THRUST
LATERAL (CENTERING) FORCE

FIGURE 1: LIM FORCES

The lift force generated by the LIM is proportional to the flux density squared and the LIM surface area. The flux in turn is proportional to the applied voltage and inversely proportional to operating frequency. At low frequencies the voltage must be boosted to account for the voltage drop due to the resistance of the LIM windings. Figure 2 shows the voltage, frequency and flux plotted against vehicle speed.

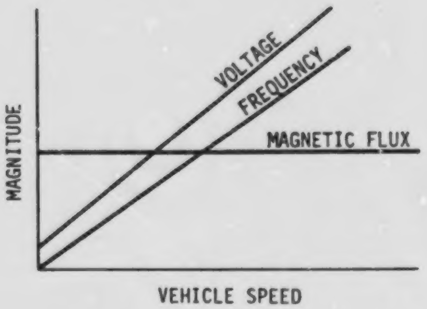

FIGURE 2
VOLTAGE, FREQUENCY, AND MAGNETIC FLUX CHARACTERISTICS

Figure 2 represents the case of constant lift force. The magnetic flux is seen to remain constant throughout the speed range. Motor current is also constant throughout the speed range for the condition of constant air gap. Control system linearization and motor impedance compensation are achieved when the LIM windings are energized at the following voltage.[1,2]

$$V_m = K_1\sqrt{F}\,\omega \cos \omega t + K_2\sqrt{F}\,G \sin \omega t$$

where

V_m = motor voltage (phases B and C are displaced 120 and 240 degrees)
F = desired lift force
ω = motor frequency (radians/sec)
t = time
G = air gap
K_1, K_2 = constants based on motor design

The IMPS concept is competitive with rubber tired vehicles in the area of energy consumption. Both vehicles require equal amounts of energy to overcome aerodynamic drag, and for grade climbing and acceleration forces. In addition, the IMPS system requires a constant power consumption for levitation whereas rubber tired vehicles require constant energy (for a given trip) to overcome rolling resistance. For average speeds of 35 MPH the energy consumption is equal. IMPS uses less energy above 35 MPH and more at lower speeds. The crossover speed depends on the operating air gap and is reduced as the air gap is reduced below 0.4 inches. Lower performance systems can operate at smaller air gaps with correspondingly lower crossover speeds.

CONFIGURATION OPTIONS

Several configuration options have been studied. The configurations can generally be divided into bottom supported and top suspended categories, each with advantages and disadvantages. In general, very high performance requirements (i.e., AGRT with its very short headways) drive the selection to top suspended. The top suspended AGRT designs can maintain levitation while performing high speed switching maneuvers, but require guideway contact for lateral positioning. Systems operating at greater headways can take advantage of the non contacting characteristics of the bottom supported designs. The bottom supported designs are expected to have superior ride comfort and to be accoustically quieter. The final configuration selection will be based upon system requirements and environmental factors. The work that is being performed on this project is applicable to either configuration.

MAJOR DEVELOPMENTS

The IMPS concept has been under development at Boeing for approximately five years. During that time the hardware development has concentrated on the LIM, Power Conditioning Unit (PCU), and control electronics.

LIM

At the time Boeing acquired the IMPS technology, a LIM design program (computer program) and a LIM were included. A test stand was fabricated and the LIM was tested. Computer program performance predictions were compared to test results and the program was updated. A second LIM was designed and tested and the program was again updated. A third LIM has been designed and is currently undergoing tests. Figure 3 shows the second LIM installed in the test stand. The LIM and reaction rail are inverted for test convenience. LIMs for vehicle use have separate windings, fore and aft. Differential excitation of these windings allows pitch control. Similarly, differential excitation of left/right motors allows roll control.

CONTROLS

The control system consists of the sensors and electronics necessary to determine the voltage that, when amplified by the PCU and applied to the LIM, will produce the desired lift force.

Two types of sensors are used in the control system. They are gap sensors and accelerometers. The gap sensors measure the instantaneous air gap. The measured gap is compared to the commanded gap and an error signal is produced. The error signal is processed to generate a lift command. The accelerometers measure vertical acceleration, which is integrated to obtain velocity and used to damp the lift command. Non contacting gap sensors of

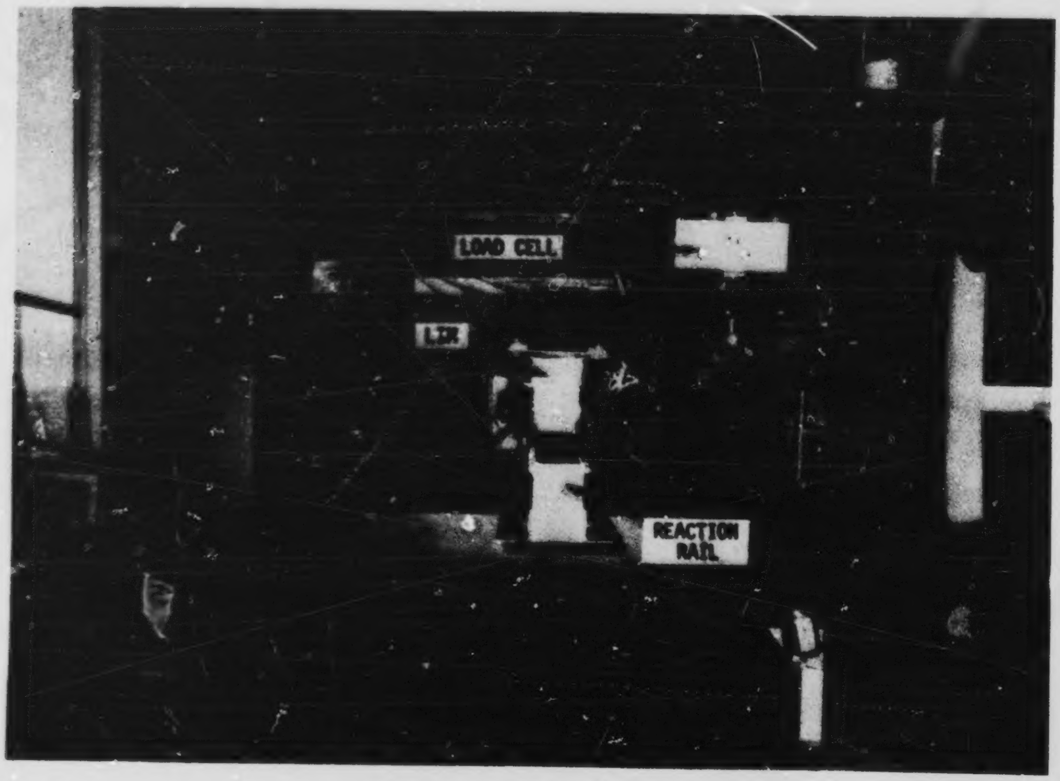

FIGURE 3: LIM AND TEST STAND

the eddy current type are being used. The accelerometers are of the servo type with built in amplifiers.

Control system electronics are divided into analog and digital types. The analog circuits process the gap sensor and accelerometer data to produce individual lift commands to each motor. The control system therefore is able to control heave (lift), pitch and roll (some configurations) independently.

The digital circuits function as a hardwired computer to perform the arithmetic functions necessary to linearize the control system, insert the frequency (speed and thrust) information, and compensate for LIM winding resistance. A state of the art design based on a microcomputer has dramatically reduced parts count while improving performance.

PCU

The primary development effort has been the PCU. The IMPS system requires the PCU to be carried on board and therefore size and weight are important. The PCU must also provide an output voltage with minimal harmonic content and/or DC currents to achieve the prescribed ride comfort. These requirements are best met with transistorized PWM inverters in the present state of technology development.

A PCU using very large state of the art switching transistors has been developed to the breadboard stage. The PCU uses 24 Westinghouse D7ST transistors. The D7ST transistor has peak ratings of 500 V_{DC} ($V_{CEO(SUS)}$) and 400 amperes (I_C). The application applies 340 V_{DC} at currents up to 220 amperes per transistor. Previous designs using TO-3 size transistors required paralleling 40 transistors for each of the Westinghouse D7ST's. The arrangement is a conventional six element, three phase, bridge inverter. Three transistors are paralleled in each position with a fourth transistor in darlington. Figure 4 shows the breadboard PCU. The PCUs are now functional and are operating at the following performance levels:

DC Bus Voltage	340 VDC
AC Output Voltage	0 to 240 VAC (rms L-L)
AC Output Current	500 Arms
KVA	200 +
Efficiency	95-96%

The PCU must operate over a wide range of load conditions including regeneration during braking. This requires a PCU capable of four quadrant operation (the voltage and current may exist in any combination of polarities). Figure 5 shows the general arrangement and the active elements during four quadrant operation.

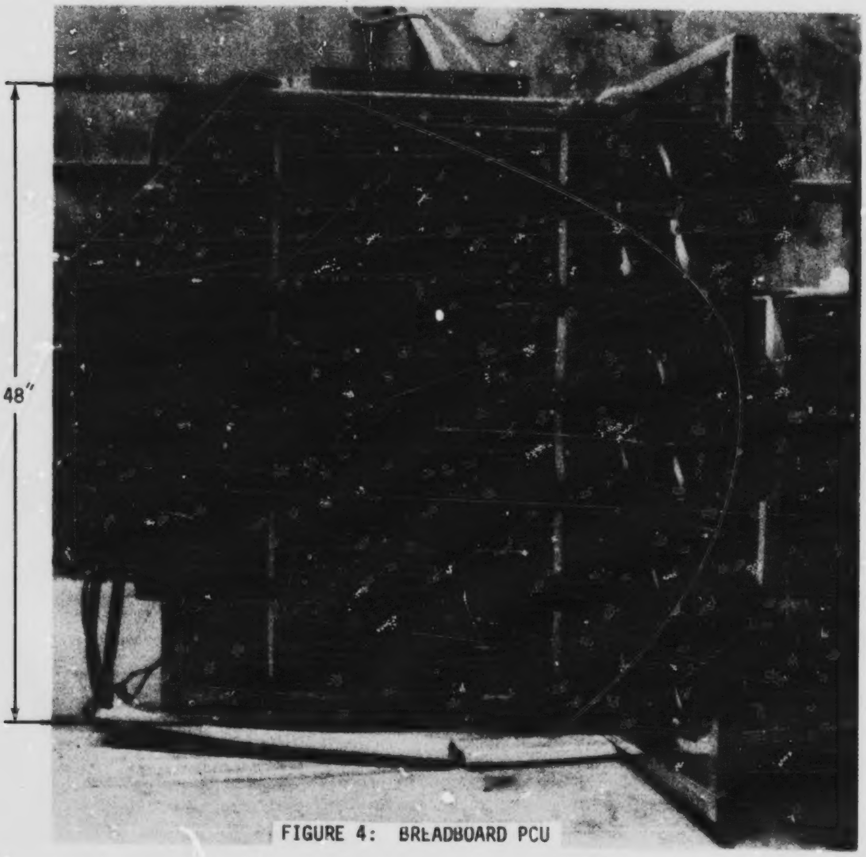

FIGURE 4: BREADBOARD PCU

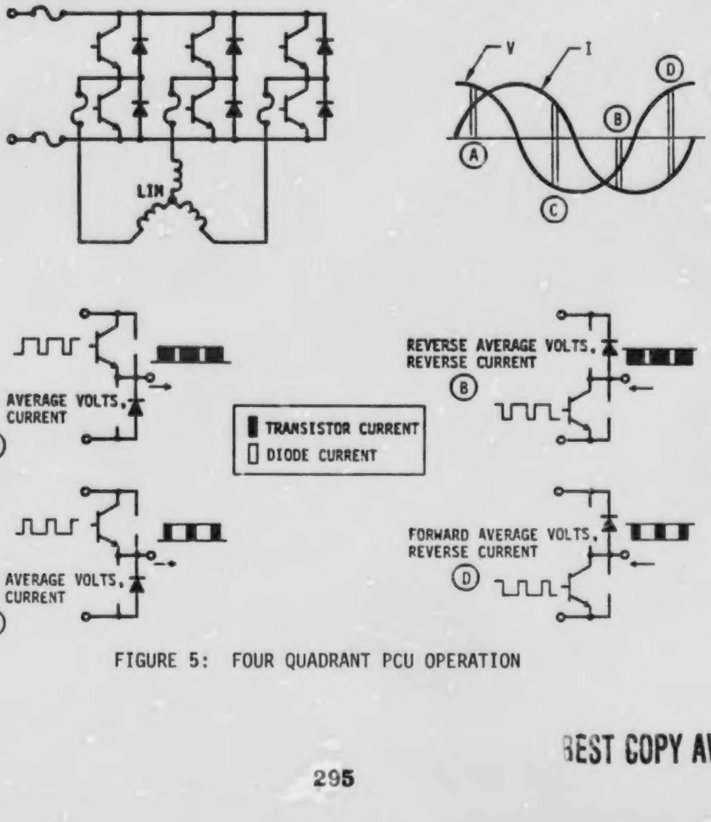
LIM
V
I
A
B
C
D
FORWARD AVERAGE VOLTS, FORWARD CURRENT
A
REVERSE AVERAGE VOLTS, REVERSE CURRENT
B
TRANSISTOR CURRENT
DIODE CURRENT
REVERSE AVERAGE VOLTS, FORWARD CURRENT
C
FORWARD AVERAGE VOLTS, REVERSE CURRENT
D

FIGURE 5: FOUR QUADRANT PCU OPERATION

The breadboard PCU's were not designed for minimum size or weight. In fact, the heatsinks were deliberately oversized to accommodate less than optimum performance. Now that proper circuit operation has been achieved, the PCU size and weight could be substantially reduced. Conservative estimates place the required volume and weight at less than 50 and 70% of the present values. These estimates are based on continued forced air cooling. Additional size and weight reductions are achievable using state of the art cooling techniques.

While most of the PCU development has concentrated on the power components, the low level logic has not been ignored. The driver logic has been redesigned in programmable array logic (PAL) with an order of magnitude reduction in chip count and interconnect wiring. The driver logic implements the following functions:

1. Minimum transistor on time
2. Minimum transistor off time
3. Minimum dead band between + and - half phases
4. Generation of a carrier frequency
5. Fault protection
6. Base drive conservation

This PCU, while developed for LIM excitation, is also suitable for a variety of variable speed motor drives. In fact, conventional AC induction motors are routinely used in testing the PCUs.

TEST PROGRAMS

The IMPS system is being subjected to a series of test programs intended to provide a progressive evaluation of performance at minimal costs. These major tests in the order of performance are:

1. Hover Test
2. Low Speed Dynamic Test
3. Bottom Supported Low Speed Dynamic Test

The hover test is in progress as of this writing. At this point data has been collected to allow evaluation of the LIM performance in the areas of:

1. Flux distribution
2. Voltage/current/flux/air gap relationships
3. Power consumption
4. Thermal performance

The hover test LIM has lifted and controlled 11,000 pounds. The control system's performance is now being tested and results will be available at the conference. Figure 6 shows the Hover Test Stand. Figures 7 and 8 show the LIM flux density distribution and winding temperatures respectively. The flux density test is at 150 amperes, 11 mm air gap and a 6 Hz motor frequency (1.2 g lift at nominal gap). The temperature data is recorded for motor currents of 100 and 150 amperes. While hovering at nominal lift (10,800 lbs) the motor current is 125 to 130 amperes. Maximum weight would increase the motor current to approximately 135 amperes.

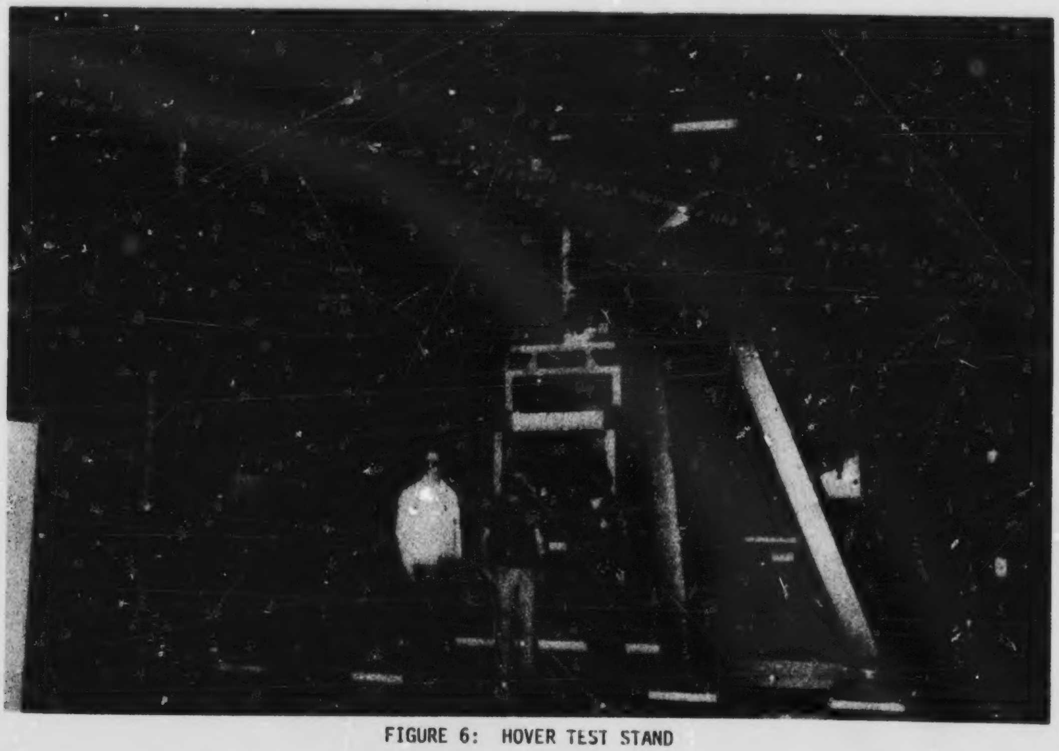

FIGURE 6: HOVER TEST STAND

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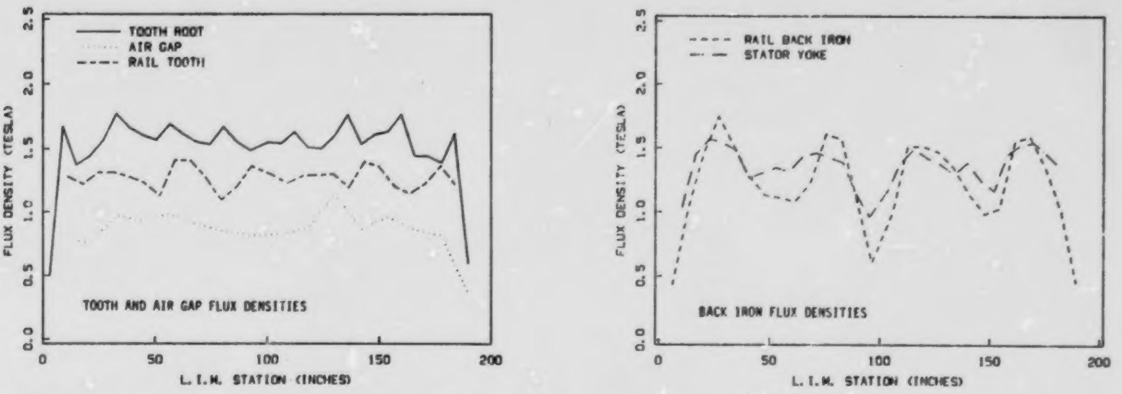

FIGURE 7: LIM FLUX DISTRIBUTION

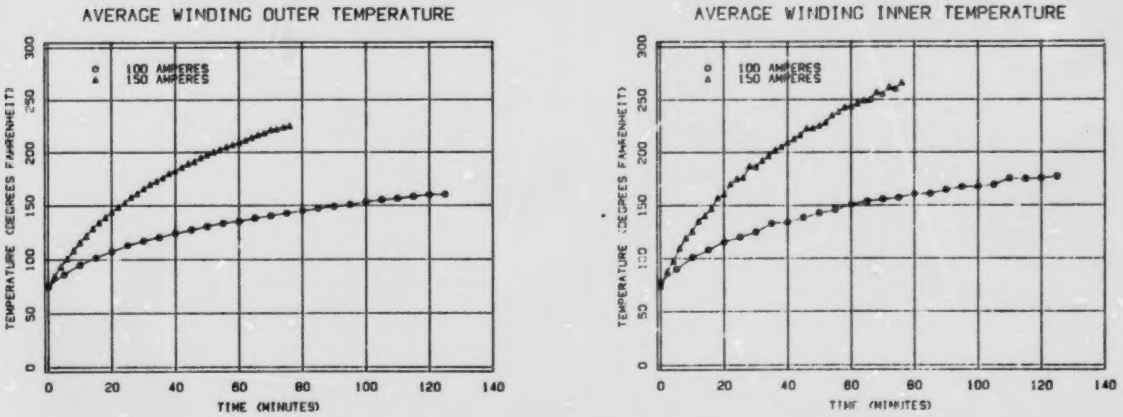

FIGURE 8: LIM TEMPERATURES

Upon completion of the hover tests, the guideway beam will be extended by welding a 70 foot extension to the test stand. This will allow low speed operation to evaluate dynamic effects of motion. For example, the control system must react the pitch moments generated during acceleration.

Finally a bottom supported configuration will be developed along with a short (approximately 90 feet) guideway segment. This configuration will undergo propulsion/suspension/control system tests producing a data base adequate to develop a prototype vehicle design.

STATUS

The IMPS program has developed conceptual vehicle/guideway designs for several configurations. The advantages and disadvantages of each configuration have been compared and two configurations are currently being evaluated.

The development program has concentrated on the LIM, PCU and control system. The LIM has experienced three iterations of design, test and evaluation. A PCU using state of the art power transistors has been developed to a functional breadboard state. Control system sensors and electronics have been developed for a non contacting system.

The hover test program is in progress and will be completed by the time of the conference. Test results will be available at the conference.

REFERENCES

1. R. G. Rule and R. G. Gilliland, "Combined Magnetic Levitation and Propulsion - the Mag-Transit Concept," IEEE Transactions on Vehicular Technology, pp 41-49, Feb., 1980.
2. R. G. Gilliland, "Mag-Transit Development at Boeing," 29th IEEE Vehicular Technology Conference Record, pp 148-151, March 27-30, 1979.

LIM PROPULSION & POWER FOR THE DETROIT DOWNTOWN PEOPLE MOVER

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UTDC
Canada

Abstract

An innovative type of linear motor propulsion is to be applied to a 3 mile downtown people mover in Detroit, opening in 1985. The LIM, mounted between the axles of a rail vehicle, is powered by a power transistor inverter of 325 KVA capacity. The inverter uses natural convection only for cooling (no fans), and uses transistors of 250 amp/750 volt power rating.

Extensive use of trackbased laminated reaction rail is made in the Detroit application, because of the unusually short station spacing and the frequent acceleration zones. Regenerative braking is employed, despite the small fleet of 13 vehicles, and line receptivity is assured by the use of an automatic wayside resistor.

The use of a LIM to provide assured automated propulsion under winter snow and ice conditions is described.

INTRODUCTION

In 1982 the South East Michigan Transportation Authority (SEMTA) selected the technology of the Intermediate Capacity Transit System (ICTS) developed by the Urban Transportation Development Corporation (UTDC) for its People Mover Transit System for downtown Detroit. When the system becomes fully operational in 1985 it will service a 3 mile loop, shown in Fig. 1, with up to twelve automated driverless vehicles which can operate singly or in pairs.

The selection of ICTS technology for this application was based on the need to meet the following requirements:

- small guideway size for unobtrusive integration into the downtown area;
- low radii of horizontal track curvature for negotiation of existing fixed facilities;
- high rates of acceleration and deceleration (up to 0.13 g);
- full service operation in severe winter conditions without recourse to special track protection or clearing techniques;
- fully automated operation;
- low noise.

The features of ICTS that enable it to meet the People Mover requirements are:

- small, lightweight aluminum vehicles;
- steerable axle steel wheel trucks;
- linear induction motor (LIM) propulsion system;
- protected and heated wayside power distribution;
- moving block automatic train control.

The correlation of requirements and subsystem performance will be amplified in the following sections.

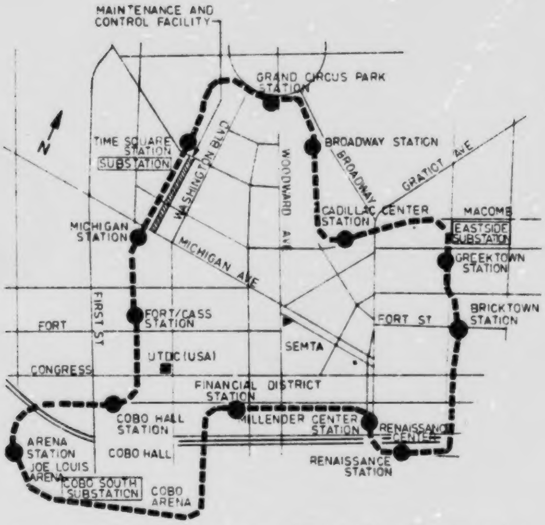
MAINTENANCE AND CONTROL FACILITY
N
GRAND CIRCUS PARK STATION
TIME SQUARE STATION
SUBSTATION
CASS
WASHINGTON BLVD
WOODWARD AVE
BROADWAY STATION
BROADWAY
GRATIOT AVE
CADILLAC CENTER STATION
MACOMB
EASTSIDE SUBSTATION
MICHIGAN STATION
MICHIGAN AVE
GREEKTOWN STATION
BRICKTOWN STATION
FORT
FIRST ST
FORT/CASS STATION
FORT ST
SEMTA
UTDC (USA)
CONGRESS
FINANCIAL DISTRICT STATION
COBO HALL STATION
MILLENDER CENTER STATION
RENAISSANCE CENTER
RENAISSANCE STATION
ARENA STATION
JOE LOUIS ARENA
COBO HALL
COBO SOUTH SUBSTATION
COBO ARENA

FIG 1 POWER DISTRIBUTION SYSTEM OF DOWNTOWN PEOPLE MOVER SYSTEM

CATS SYSTEM

SEMTA's Downtown People Mover System will consist of driverless vehicles travelling along a single track on an exclusive guideway. The guideway is elevated 15 feet or more above street level. Vehicles travel singularly or coupled together as two car trains, and operate in a closed path loop with all vehicles travelling in the same direction making all station stops before returning to the point of origin. The vehicles are compact train cars, each having a maximum capacity of 123 including standees. The cars operate at speeds of upto 30 miles per hour, with an average speed of 12 miles per hour. Stations are close spaced, with an average of 1/4 mile between platforms.

The system will be in operation by late 1985. The route, around the central business district of downtown Detroit, is 2.98 miles long, with 13 station stops at key activity centres along the loop shown in Figure 1. Several of these stations will be integrated with new or existing structures, such as the Renaissance Center. Including stopping time at each of the 13 stations, it will take each car or train about 14 minutes to complete the entire loop. During peak periods, there will be a 90 second headway between trains.

Stations will be 80 feet long, with glass walls on three sides and a wind screen along the platform edge for waiting passenger comfort. There will be stairs and an escalator at each station for the general public and elevators to be used by the elderly and handicapped. Two wheelchair tie-down spaces are provided in each car. Stations will be unmanned.

Fare collection will be by token only, with dispensers for flat fare tokens at each station. A token placed in a turnstile will permit entry into the system.

A control centre and elevated, automated yard is provided adjacent to the Times Square station. The control room will be the nerve centre for all data communications, system surveillance, train operation and patron communication and assistance.

Lightweight vehicles of welded aluminum construction are used, 13 in all. Each vehicle is 42' long, 8' wide and 10' high. Cars are air conditioned for patron comfort, and are propelled by truck mounted linear motors (2 per car). Tare car weight is less than 15 tonnes. Perimeter seating for 30 passengers is provided, with flip up seats for wheelchair parking. Secondary suspension is by means of solid rubber 'hemisphere' springs, while primary suspension uses rubber rings around the axle bearing. Steel wheels of 18" diameter are pressed onto solid steel axles, two axles per truck, two trucks per vehicle.

ICTS DESCRIPTION

AUTOMATIC TRAIN CONTROL

The SELTRAC moving block system is used for all train automatic operation, protection and control. This system utilizes an on-board microprocessor, linked to central computers via an inductive loop laid between the running rails. It permits close headway between trains and facilitates the design of the fully automated storage yard. All switch interlockings are controlled by the SELTRAC system, which uses computer software in a vital safety role.

STEERABLE TRUCKS

Trucks are of an innovative design featuring axles that are steered by connection to the carbody, to minimize steel wheel noise and squeal on curves. The People Mover route uses frequent 35 metre (115 ft.) radius curves, to allow the track to traverse city street corners. Extensive use of light alloy in the truck sideframes, bolster and axle housing minimizes unsprung weight. The linear motor is suspended directly from the axle/steering arm assemblies.

LINEAR INDUCTION MOTORS (LIM)

The linear induction motors used for propulsion are shown diagrammatically in Figure 2. The normal mean clearance between the working face of the primary and the track reaction rail surface is slightly less than a half inch.

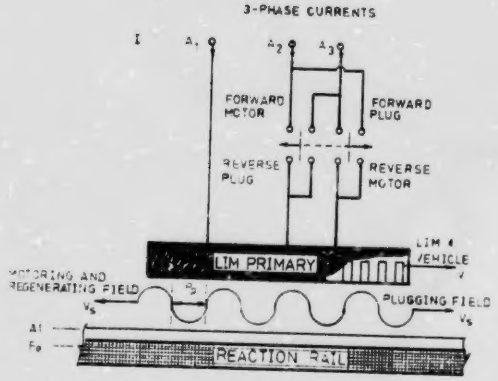

FIGURE 2. LIM SCHEMATIC DIAGRAM

The primary consists of a lamination stack of magnetic steel "combs". The large magnetic gap at which the motor has to operate results in low flux densities from high magnetizing currents, compared with conventional rotary motors. The design, therefore, has relatively slender magnetic circuits and deep winding slots. The three phase, wye-connected windings are of conventional diamond coil formation. However, the discontinuous nature of the LIM results in half filled slots at the extremities of the lamination stack. Lateral envelope constraints, because of other truck-mounted equipment, have enforced the use of 7/12 pitch coils: unusually low for induction motor design. Cooling for the primary is provided by a set of ten "pancake" axial fans integrally mounted to the top of the motor. The area of major heat extraction is the endwindings, the production of which is critically controlled to ensure air flow passages. The class H insulation allows hot-spot temperatures of 220°. The motors are designed for normal maximum service operation of 150° with reduced power operation being instigated if an indicated 180°C is reached.

The secondary, or reaction rail, consists of a 0.165 inch thick aluminum sheet mounted firmly on top of, but not connected to, one of the two forms of steel. The aluminum sheet provides the electrical circuit of the motor secondary; equivalent to the cage of a conventional induction motor. The selection of the appropriate grade of aluminum for particular applications has been discussed in a previous paper (1). The underlying steel, or "back-iron", completes the magnetic circuit required by the primary. In track zones which demand high acceleration, the "back-iron" is a coarse lamination stack formed from ten one inch square steel bars mounted longitudinally in approximately 10 ft. sections. Elsewhere, in zones of lower performance requirement, a more economical "back-iron" of half inch solid mild steel sheet is adequate. The relative performance of the two configurations is shown in Figure 3. The aluminum top cap and steel back-iron are separated by a plastic film which provides a corrosion barrier between the dissimilar metals and, having a very low coefficient of friction, assists relative motion during thermally induced periods of expansion and contraction. Details of the LIMs are given in Table 1.

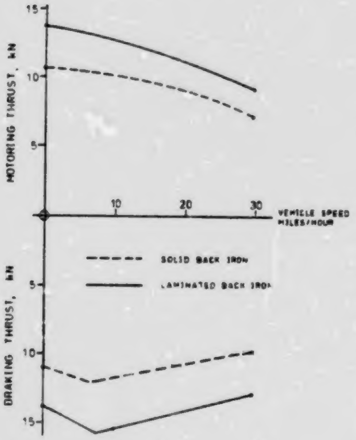

FIGURE 3

In order to achieve the described performance, it is necessary to control not only the magnitude of the motor currents but their slip frequency. For the most part a slip frequency in motoring of plus five hertz is specified. In braking, minus five hertz is applied between full speed (30 mph) and approximately 6 1/2 mph, at which speed d.c. is called for. Below this speed the vehicle will be brought to rest electrically by reversal of the phase sequence and use of the plugging mode of operation, drawing power from the wayside.

Table 1 - Details of LIM Propulsion System

1.	CORE CONSTRUCTION	
	Active Length	1896mm
	Active Width	216mm
	Active Depth	99mm
	Number of Slots	79
	Basic Weight	202kg
2.	WINDING DETAILS	
	Number of Phases	3
	Number of Poles	6
	Pole Pitch (Slots)	12
	Coil Pitch (Slots)	7

Slots/Pole/Phase	4
Turns/Coil	4
Endwinding Overhange (per side)	152mm
Conductor-Copper (1.72 microhm-cm at	 25°C)
Conductor - CSA	62.2mm²
Connection - Series WYE	
Winding Type - Diamond, Two Layer (end slots half full)	
Insulation - Class H	
Basic Weight (Copper only)	217kg

3. REACTION RAIL

Sheet Conductor - 6351 - T6 Extruded Aluminum (3.5 microhm-cm)	 25°C)
Sheet Thickness - Over Back Iron	4.5mm
Sheet Thickness - Equivalent End Bar Area	18mm
Sheet Width	325mm
Back Iron Depth (Solid Sheet)	240mm
Back Iron Depth (Laminated)	25.4mm

POWER CONDITIONING UNITS (PCU)

The variable voltage, variable frequency supply required to optimise the performance capabilities of the LIM, will be provided in the People Mover vehicles by pulse width modulated inverters. In order to achieve the specified system availability it is necessary to provide two independent inverters per vehicle; i.e., one per motor.

The PCU's selected for this application, because of low weight and volume, and capability to be cooled by convection alone, utilize the Westcode WT 5702 transistor.

Each leg of each phase of the inverter employs three parallel groups of two series connected transistors; each level of three transistors requires a further identical transistor to provide the base drive current. This results in a total of sixteen transistors per motor phase.

Control of the slip frequency at plus or minus five hertz, depending on motoring or braking mode, is achieved by appropriately scaling a tachometer signal and adding or subtracting the reference frequency to determine the required inverter frequency. For a given operating condition the motor thrust is directly proportional to the square of the current. Consequently the necessary increments of inverter output current are determined by comparing the square root of a thrust command with the LIM phase currents.

During normal service braking the propulsion system returns energy via the inverter to the d.c. wayside supply. If no suitable load is present to absorb this energy the voltage at the d.c. terminals of the inverter would rise, possibly to a level that could damage components. Such overvoltage conditions are guarded against by the use of a wayside energy absorption system and by inverter control. The former will be described in Section 3.6. When the safe operating voltage limit is sensed by the inverter, the slip frequency is increased to reduce the regenerated energy and avert the hazardous condition.

A simplified block diagram of the inverter control system is shown in Figure 4.

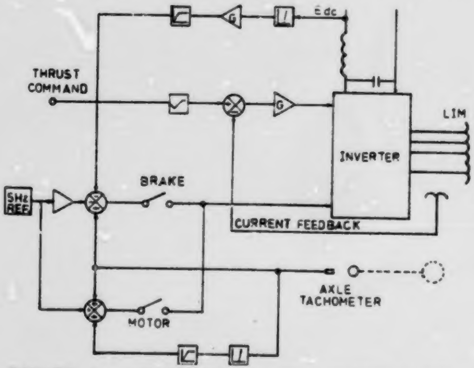

FIGURE 4. SIMPLIFIED CONTROL BLOCK DIAGRAM

POWER COLLECTION AND WAYSIDE DISTRIBUTION

The majority of steel wheel/steel rail transit systems employ current return, from vehicles to substation, via the running rails. Generally, the rails are held at, or close to, ground potential to avoid electric shock hazards at the vehicles. This philosophy creates the possibility of leakage and/or circulating currents in nearby metallic components and structures. These currents can, unless controlled, cause electrolytic corrosion.

To avoid this possibility, it was decided that the CATS vehicles would be maintained at a safe potential by grounding of the running rails at stations and at approximately 350 foot intervals along the alignment. Current return does not utilize the running rails. A separate positive supply, and negative return, wayside conductor system is to be employed. This will be referenced to ground via resistors of sufficient impedance to limit any return currents, that could occur in unusual operating conditions, to tolerable levels. Referencing of the supply to ground is necessary to prevent an otherwise floating 600 Vdc wayside supply drifting to unsuitable voltage levels. An additional advantage offered by the dual pole ungrounded power distribution system is that a single insulation breakdown or failure does not cause fault currents to flow which would result in service interruptions or disabling of the vehicle.

In order to provide a two conductor system in a compact guideway, which already contains LIM reaction rail and ATC cables, it is necessary to employ higher conductivity material than the conventional steel third rail. Consequently, aluminum conductors with stainless-steel operating faces have been chosen for CATS. The system requires that the conductors be on the outside of low radius track curves in order to maintain safe clearances to vehicle underfloor equipment. This, in turn, requires frequent conductor ramps as power is transferred from one side of the guideway to the other. Within the envelope constraints these considerations favour a side running collector system, although this introduces a tendency to ice formation in freezing rain storms, when compared to an under-running third rail.

In 1982 a series of experiments was conducted for UTDC in the low temperature research laboratories of the National Research Council of Canada, in Ottawa. The experiments addressed the problem of providing an adequate anti-icing system, consisting of heaters and coverboards, for the power distribution conductors. The available space and vehicle dynamic envelope place strict constraints on the coverboard design which is needed for three functions: to reduce the amount of direct precipitation to the conductor operating surface; to reduce heat losses from the back of the conductor and hence increase the effectiveness for the heaters; to prevent inadvertant contact with the conductors by maintenance personnel.

The design developed is shown in Figure 5 and is used in conjunction with a self limiting heater of 20 watts/foot dissipation installed in runs of up to 350 feet. This heater uses a 'smart' semiconductive polymer, which automatically increases heating up to 32 watts foot in more severe cold weather.

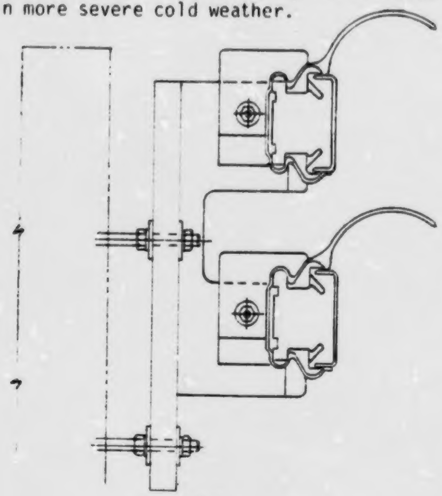

FIGURE 5

The vehicle collector shoes will also have provision for the attachment of heaters, should these prove necessary. The collectors employ shoes of three carbon blocks set in a bronze housing. Collector sets are located on each side of both trucks. The dual collector arms are independently tensioned, to provide a contact force in the range 25-30 lbs. over an active area of approximately 16 square inches. The collector tension is provided by torsional rubber springs. Both collector arms in every assembly are independently fused to protect against faults of any polarity.

SUBSTATIONS

Power is to be provided to the System mainline and maintenance/storage facility from three substations located at Times Square, Eastside and Cobo South, as shown in Figure 1. For at least five years, before final line capacity is reached, only the substations at Times Square and Eastside will be connected, providing 1.25 MW each to the mainline. The 1.25 MW rated Cobo South substation will be added when system density increases to the final rating.

As part of the CATS power distribution system design a load flow and energy management model, developed at Carnegie - Mellon University, was adapted by members of UTDC and Queen's University to describe LIM propulsion and the Detroit alignment. These studies confirmed the adequacy of the substation equipment and the wayside conductor system to meet the anticipated loads within the required voltage range.

All three substations will be monitored and controlled from a supervisory control and data acquisition system (SCADA) located in central control in the Times Square Station.

A single line diagram of the positive polarity equipment in the Central (Times Square) Substation is shown in Figure 6. The negative polarity equipment, which is not shown will be an image of the positive configuration. Separate positive and negative switchboards will be provided. However, slaved contactors in the negative may replace the positive breakers for reasons of economy.

The substations will be supplied by the Public Lighting Department of the City of Detroit at 4.8 kV. A 15 kV rated a.c. switchboard will contain regular and standby incoming breakers to accept two independent supplies. A breaker and two motorized disconnects will supply various loads in the substation and the vehicle Maintenance and Cleaning Facility (MCF). 600 Vdc power will be made available to the storage tracks and the maintenance access tracks via a 300 KW 6-pulse transformer/rectifier unit and a 750 Vdc rated switchboard. This MCF d.c. supply can be connected to the main propulsion power system at times of failure or maintenance. Propulsion power to the guideway is to be provided by a twelve pulse, ANSI 31 circuit transformer rectifier and controlled by a d.c. switchboard. The switchboard feeders supply the northbound guideway, southbound guideway, the guideway isolation zone and the automatic assured receptivity unit (AARU) used for regenerative braking.

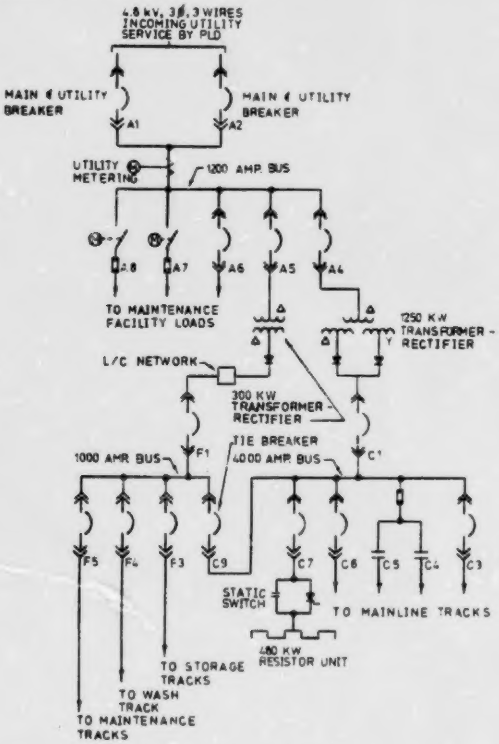
4.8 kV, 3Ø, 3 WIRES INCOMING UTILITY SERVICE BY PLD
MAIN ⊄ UTILITY BREAKER
MAIN ⊄ UTILITY BREAKER
A1
A2
UTILITY METERING
1200 AMP. BUS
A8
A7
A6
A5
A4
TO MAINTENANCE FACILITY LOADS
1250 KW TRANSFORMER - RECTIFIER
L/C NETWORK
300 KW TRANSFORMER - RECTIFIER
TIE BREAKER
1000 AMP. BUS
4000 AMP. BUS
F1
C1
F5
F4
F3
C9
C7
C6
C5
C4
C3
STATIC SWITCH
TO MAINLINE TRACKS
480 KW RESISTOR UNIT
TO STORAGE TRACKS
TO WASH TRACK
TO MAINTENANCE TRACKS

FIGURE 6. CENTRAL SUBSTATION

Each pole of the guideway isolation zone consists of two conductor sections of approximate length 13 1/3 feet, electrically isolated from each other and from the otherwise continuous conductor bar system. The joints providing electrical isolation and mechanical continuity are long enough to prevent bridging by a collector shoe. This arrangement enables the sections of the wayside power distribution system to be isolated without danger of reconnection by the passage of vehicles across the isolation zone. During normal operation the short sections are fed by contactors of relatively low rating. This isolation feature is provided to enable equipment maintenance and to facilitate the tracing of failures of system insulation to ground from either positive or negative poles on either wayside or vehicle equipment.

The AARU is fed from its own breaker and, as was mentioned in Section 3.4, serves to prevent excessive d.c. system voltages during periods of vehicle regenerative braking. In the event of the voltage threshold of 690 Vdc being detected, a thyristor will be fired to connect a 480 kW load resistor between the positive and negative buses. Shortly afterwards, a contactor in parallel with the thyristor is closed to conduct the bulk of the dumped energy into the resistor and to commutate the thyristor. The system is provided with an adjustable timer which opens the contactor to determine if the period of regeneration excess is over.

It is recognised that the above process represents a waste of energy and that some power will be drawn by the AARU resistor from the substation rectifier as well as from the decelerating vehicle(s). However, the frequency of AARU operation is anticipated to be very low. When the system is operating normally there will always be other vehicles to absorb the regenerated energy, even with the power distribution system sectionalized. Operation of the AARU should only occur during system start-up or shut-down when few vehicles are operating on the mainline guideway. Even under these low traffic densities, in winter periods the regenerated energy may be absorbed by the power rail heaters and hence do useful work.

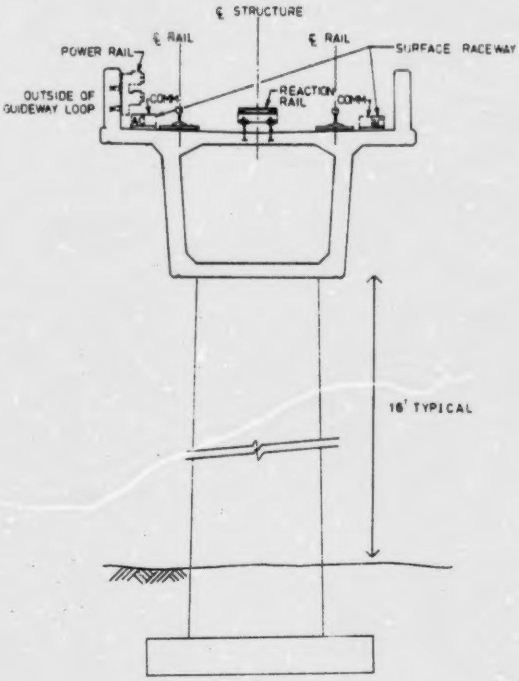
⊄ STRUCTURE
⊄ RAIL
⊄ RAIL
POWER RAIL
SURFACE RACEWAY
OUTSIDE OF GUIDEWAY LOOP
COMM.
REACTION RAIL
COMM.
AC
16' TYPICAL

FIGURE 7 : GUIDEWAY CROSS-SECTION

GUIDEWAY INTEGRATION

Compared with more conventional transit systems the CATS will have more guideway equipment to be contained in the small cross section of its elevated concrete beams. The relative size and location of the equipment described in this paper is shown Figure 7.

PROPULSION PERFORMANCE

The People Mover system is of special note, compared to other ICTS installations in Toronto and Vancouver, because of its short station spacing. As a consequence, a Detroit vehicle spends a major portion of its time in motion accelerating or braking, with very little time actually cruising at the 30 mph design speed. All components have been rated for this relatively severe duty and projected RMS current in the linear motor is within the continuous design loading of 360 amps.

A typical route profile between Financial and Millender stations is shown in Figure 8 . It can be seen that the linear motor is producing full accelerating thrust 1/3 of the time, cruising at 7% thrust 1/3 of the time, and braking at full thrust for the remaining 1/3. Put another way, the motor is running at full thrust for nearly 70% of the time. For this reason, 54% of the CATS route has high performance laminated reaction rail, the remainder being solid reaction rail. For comparison, a recent line haul application of ICTS used 20% laminated reaction rail.

Laminated reaction rail enables higher motor efficiencies at speed, and consequently a greater thrust for the same PCU maximum output of 485 amps rms. Thus the thermal duty on the linear motor is actually reduced, since less time is spent accelerating to cruise speed.

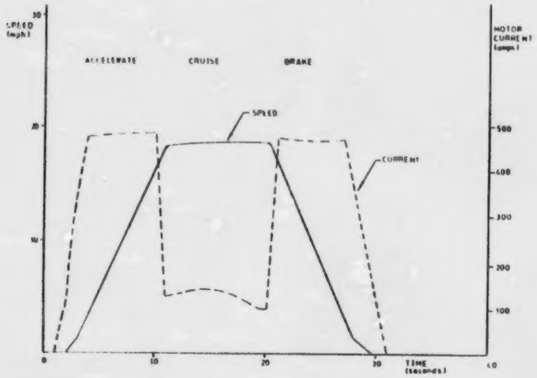

FIGURE 8 TYPICAL MOTOR DUTY CYCLE

CONCLUSIONS

The use of linear motor propulsion for the Detroit People Mover has enabled all weather steel wheel/rail technology to be used, with relative independence from wheel slip/slide adhesion problems. This independence has facilitated the application of automation.

The use of semi-conductive power rail heating has made possible a simple and reliable control system for keeping the power collection rails ice free.

Energy consumption is improved by the use of regenerative braking, feeding power from decelerating vehicles back into the power rail to be used by other vehicles.

ACKNOWLEDGEMENTS

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REFERENCES

(1) A.K. Wallace, "The Function of the Reaction Rail in the Development of a LIM Propulsion System for Urban Transit", IEEE IAS Annual Meeting, October 1982, San Francisco.

M-BAHN — ADVANCED MAGLEV TECHNOLOGY REALITY

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SUMMARY

The M-BAHN is the world's most advanced magnetic leviation public transit system and more importantly, it is a reality! This system makes all other transit systems obsolete.

The M-BAHN has been invented and is being produced by the MAGNETBAHN Company GmbH, Starnberg, West Germany, which specializes in transport systems. In Germany several companies have studied possible solutions to the budgetary, energy, and environmental problems of mass transit being faced by all governments worldwide. The M-BAHN was selected as the winner of the competition by the Ministry of Research and Technology of the Federal Republic of Germany and is the only Mass Rapid Transit System (MRT) actually being funded by the German government. The M-BAHN is now ready for increased public transit use after years of extensive testing.

The functioning principle of M-BAHN is the levitation of vehicles by Permanent Magnets and moved by an Electromagnetic Travelling Field generated in the fixed guideway. The vehicles, therefore, have NO motors inside nor weight carrying wheels. This means a considerable reduction of vehicle weight (by more than 50%) resulting in lighter guideway construction and less energy consumption (by 65%). Operational costs are substantially reduced because the system was conceived and designed for fully automatic operation. No moving parts in the vehicles and a fixed manufactured guideway without ties and ballast drastically reduce maintenance costs.

This presentation provides a technical description of the principle, the vehicles, the guideway and station layout, system operation, system characteristics, and current status.

DESCRIPTION OF PRINCIPLE

There are two significant and fundamental differences between the M-BAHN System and conventional rail transit systems. These M-BAHN differences are so basic and important that they result in major contrasts in construction, operation, and maintenance characteristics. The two differences in the functioning principle of the M-BAHN are:

1. The vehicle and passenger weight is carried by permanent magnets instead of by steel wheels on steel rails.
2. The propulsion is accomplished by a long stator motor in the fixed guideway instead of by rotating motors aboard the vehicles.

WEIGHT CARRYING

The M-BAHN provides a new application of the old principle of magnetism resulting in a unique State-of-the-Art technique. Permanent magnets are installed at the upper part of the vehicle undercarriage (two bogies) and act against the steel guideway structure and the long stator, thus providing the necessary force to levitate the vehicle. The magnetic force is controlled mechanically over the air gap as a function of the actual payload by a simple system using the guidewheels. Thus the attracting force of the magnets is kept equal to the vehicle weight at any time. The vertical guide wheels therefore do not carry any load except for small nonlinear residual forces and dynamic forces due to guideway misalignments. It is the purpose of the vertical guide wheels to make contact with the guiderails as a reference for air gap control. The air gap typically varies between 1.5 and 3.0 centimeters.

The permanent magnets installed on the vehicles at the M-BAHN test facility in Braunschweig, Germany, have been successfully utilized during more than six years of extensive testing and daily operation. There has been no measurable decrease in the magnetic force of the permanent magnets on these operational test vehicles during this period. Life expectancy is higher than the service life of the vehicle itself and the materials can be fully recycled. The share of vehicle empty weight allocated to the permanent magnets is about 1.2%. Material used is SmCo with alternative materials available.

PROPULSION

The M-BAHN propulsion system is accomplished by a long stator motor installed in the fixed guideway. The permanent magnets in the vehicle undercarriage have alternating polarization. Propulsion occurs when the electromagnetic travelling field provides polarization corresponding to the polarization of the permanent magnets. The electromagnetic travelling field is generated by the three phase frequency (vehicle speed) and amplitude (thrust) controlled current in the electrical cable laid within the guideway.

The M-BAHN propulsion system works as a synchronous motor. Vehicle speed is a function of the current frequency. The frequency is increased for accleration and decreased for deceleration. The necessary thrust is a function of payload and is provided by the corresponding current amplitude. The exciter field is provided by the permanent magnets installed in the vehicle undercarriage while the control function is over a sensor feedback system. The power supply is provided by stationary three phase invertors through section switches to consecutive parts of the guideway.

Driving Dynamics

The M-BAHN speed for intra-urban (metropolitan area) transit service with relatively short distances between stations is typically 10 - 20 M/S (22 to 50 MPH). In suburban or regional type transit service, the speed of M-BAHN is in the range of 75 MPH, depending on the frequency and distance between stations. Tests indicate that substantially higher speeds on the order of 125 MPH are entirely possible without guidance system modification. Changing from a mechanical guidance system to electromagnetic guidance could dramatically increase the M-BAHN inter-city speeds.

There are no apparent technical limits to operational acceleration, operational deceleration or emergency deceleration. Rather, the limitations to acceleration and deceleration are due to consideration of passenger comfort and passenger transport regulations. The operational acceleration of M-BAHN is typically about 3.3 ft./s/s with a maximum (for passenger comfort) of 4.9 ft./s/s. Operational deceleration typically is about 3.3 ft./s/s with a maximum of 8.3 ft./s/s. By comparison maximum emergency deceleration is on the order of 9.8 while typically it is about 5.2.

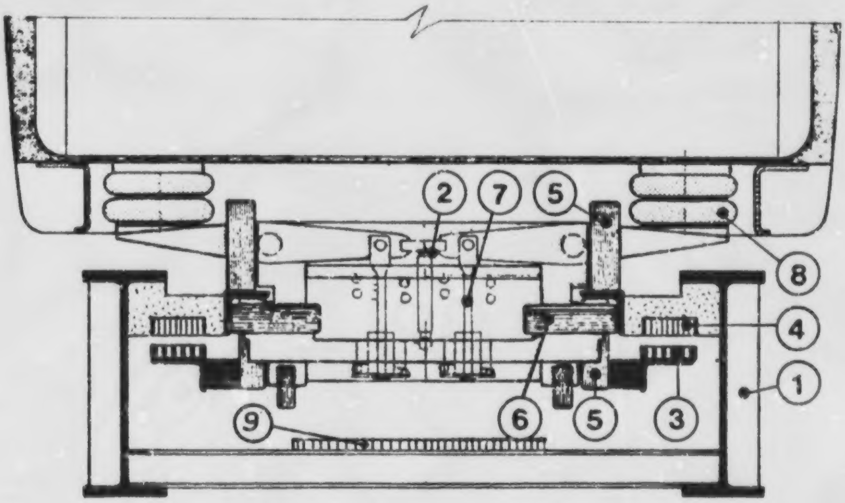
VEHICLES

VEHICLE DESCRIPTION

M-BAHN vehicles consist of a cabin and two bogies (undercarriage). The main part of the cabin is made of a light weight metal construction with the front and rear parts made of fiber glass.

The cabin has two pneumatically operated swing slide doors 1.6 M wide to accommodate the handicapped on each side with automatic closing mechanism. In addition there is a manually operated emergency door on both the front and rear end of the cabin. The power supply for the cabin is provided via a power rail in the guideway that is inaccessible to assure safety.

The main installations in the vehicle are:



VERTICAL CUT THROUGH VEHICLE AND GUIDEWAY

1.	GUIDEWAY STRUCTURE	5.	VERTICAL GUIDE WHEELS
2/7	MECHANICAL AIR GAP CONTROL AND PRIMARY SPRING SUSPENSION	6.	HORIZONTAL GUIDE WHEELS
3.	PERMANENT MAGNETS	8.	SECONDARY SUSPENSION (AIR SPRING)
4.	TRAVELLING FIELD STATOR	9.	EMERGENCY ESCAPE PATH

- o Seats (number is function of vehicle type)
- o Lights
- o Pneumatic system for operation of the doors and the emergency brake
- o Emergency brake is a friction brake working against the guideway
- o Heating and/or air conditioning
- o Two-way communications between the cabin and stations and the control center

Different vehicle types are available with the capacity adapted to meet the customer's need. Extensive studies, however, have shown that the best compromise between economy and capacity is a 70 passenger vehicle: M-BAHN TYPE M70/2. The main characteristics for vehicle type M70/2 are:

o Normal Capacity	70 Passengers
o Seats/Standing Places	24/46
o Maximum Peak Capacity	88
o Length (over all)	38 ft. 7 in.
o Width	7 ft. 7 in.
o Height (without bogie)	7 ft. 7 in.
o Empty Weight	17,199 lbs.
o Empty Weight per Place	245 lbs.
o Payload	14,994 lbs.
o Maximum Gross Weight	33,075 lbs.
o Width of Side Door	5 ft. 3 in.
o Height of Side Door	6 ft. 5 in.

VEHICLE ON THE GUIDEWAY

The vehicle of the M-BAHN System is fitted into the guideway in a way that it cannot move away from it. Therefore, derailment is impossible.

The vehicle weight is carried by permanent magnets mounted on the bogies which have a negative force against the guideway. The vehicle is guided in the guideway by vertical and horizontal indestructable guidewheels. In stabilized straight forward movement, these guidewheels do not receive a force.

GUIDEWAY AND STATION LAYOUT

The characteristics of the M-BAHN System provide extreme flexibility at low construction costs. Guideway routes can be selected to provide maximum service per mile since the system can be:

- o Elevated, on single or double tracks mounted on one row of small pillars (3 ft. 1 in. square)
- o At ground level on the surface
- o Or in a tunnel

Because of this flexibility, the M-BAHN is suitable for use in medians of highways or along street rights-of-way, adjacent to buildings, parallel to railroads or in other locations which minimize right-of-way costs.

The technique used provides additional flexibility in guideway design. The minimum turning radius is 25 M (82 ft.) made feasible because vehicles cannot be derailed. Grades of 25% or greater are possible but are generally limited to 10% grades for passenger comfort. The typical grade limitation for friction wheels on rail is 4% to 6%. Increased available grades for the system may be used to cross freeway bridges or provide access to stations.

Several construction types for guideway structures and pillars are available and have been proven with steel and concrete having been tested with success.

The small dimensions of the pillars (3 ft. 1 in.), the short radius needed, and the gradeability of M-BAHN make it the ideal multi-purpose MRT system for use in intra-urban as well as suburban public transit service.

The length of stations is dependent upon the number of vehicles to be operated in trains. Stations will normally be on-line. However, off-line stations are possible to permit the flow of traffic past the station unhindered by vehicles stopping to pick up or discharge passengers. Train operation at the stations is normally automatic, with TV control at each station and in the M-BAHN Control Center (MCC). Automatic announcements and train release are standard. The normal station equipment includes ticketing machines, train destination indicators, and the like.

SYSTEM OPERATION AND CHARACTERISTICS

OPERATIONS

The M-BAHN System can be operated over any network of lines. Connections can be made to existing railway systems by line crossing at stations or utilizing existing station platforms. Thus it is feasible and desirable to integrate the M-BAHN System with other existing transit systems. This approach is currently being used in the new M-BAHN construction in Berlin, Germany.

The M-BAHN System features decentralized automatic train operation and safety system with central control in the M-BAHN Control Center (MCC). Each train or single vehicle movement has automatic driving profile control using a central micro-computer.

The guideway track is divided into specific sections of about 200 M (220 yds.) which are connected to the power supply when a train is in the section. At the same time, the sections in front of and behind the train are disconnected from power providing a Safety Block ("Fail Safe") System. Rear end or head on train collisions are therefore prevented by unpowered sections surrounding the train. Of course, there is the possibility of a manual override from the MCC.

Problems are avoided or solved by voice communications between all trains and stations and the MCC in both directions.

Maintenance and repairs are conducted in the M-BAHN Maintenance Center (MMC) which (1) centralizes all maintenance and repair tasks for the system (rolling stock and stationary equipment) and (2) serves as siding storage for vehicles not in use. The size of the MMC has to be adapted to the number of vehicles in service and the length of the line system.

SYSTEM CHARACTERISTICS

Among the M-BAHN System characteristics are:

- o CAPACITY

The System Transport Capacity (Passengers / Hour X Direction) is a function of the train length (number of vehicles) and the headway (time interval between trains). For the M-BAHN System there are no limitations to the train length, but in all known cases not more than 6 vehicles per train are necessary.

Headway for M-BAHN is limited mainly by stopping time in the stations, which typically runs 15 to 20 seconds. The lowest suggested headway is 90 seconds except in extreme cases in which it could be as low as 60 seconds.

- o ENERGY CONSUMPTION

The energy consumption for train movement of M70/2 vehicles with a median number of passengers in a typical urban area is only about .96KWH per vehicle per mile -- very low and cost effective.

- o NOISE EMISSION

The M-BAHN System is very quiet. The noise level measured at a distance of 25 M from a passing train is about 53 DBA (DIN).

- o SWITCHING

The M-BAHN System uses the active type switches. The Active Switches are built into the guideway and are electro-hydraulically operated.

M-BAHN CAPACITY
PASSENGERS PER HOUR IN ONE DIRECTION
NORMAL AND PEAK OPERATIONS

VEHICLES IN TRAIN		HEADWAY			
		90 SEC.	120 SEC.	150 SEC.	180 SEC.
1	Normal	2,800	2,100	1,700	1,400
	Peak	3,500	2,600	2,100	1,800
2	Normal	5,600	4,200	3,400	2,800
	Peak	7,000	5,300	4,300	3,500
3	Normal	8,400	6,300	5,000	4,200
	Peak	10,600	7,900	6,300	5,300
4	Normal	11,200	8,400	6,700	5,600
	Peak	14,100	10,600	8,400	7,000
5	Normal	14,000	10,500	8,400	7,000
	Peak	17,600	13,200	10,600	8,800
6	Normal	16,800	12,600	10,000	8,400
	Peak	21,100	15,800	12,600	10,600

ADVANTAGES OF M-BAHN

The functioning principle of M-BAHN -- magnetic levitation for carrying the weight and propulsion by an electromagnetic travelling field -- results in significant weight reduction and provides the M-BAHN System with many advantages over conventional MRT rail systems. Among the major advantages are the following:

1. M-BAHN vehicles, levitated by permanent magnets and propelled externally, have:
   - (a) No weight carrying steel wheels.
   - (b) No propulsion power supply in the vehicle.
   - (c) No power converters.
   - (d) No rotating or linear motor.

2. The vehicle structure can be lighter because it has less weight to carry. A M-BAHN vehicle, M100/2, with a normal capacity of 80 weighs about 20 tons less than a conventional light rail vehicle with similar capacity. This is a weight reduction of 66%.

3. The load distribution on the track for M-BAHN is reduced by a factor of 7 (580 KP/M for M-BAHN and 4130 KP/M for conventional light rail). This results in a dramatic reduction in

guideway construction cost and specifications.

4. System weight reduction leads to significant reductions in energy consumption for propulsion. For example, only about 1 KWH is required to move an M-BAHN vehicle one mile compared to 2.7 KWH to move a comparable light rail vehicle a mile. This is a energy reduction of 65%.

5. Noise level is considerably reduced for M-BAHN. A light rail trail is measured at 63 DBA while M-BAHN is 53 DBA, resulting in an impression of the M-BAHN being half as noisy.

6. The system operation for M-BAHN is fully automatic with central control and guidance, yielding significantly lower personnel requirements.

7. The simplicity of the M-BAHN vehicles (no moving parts) leads to a much lower cost for maintenance (by a factor of 4).

8. The maintenance of stationary installations is eased by built-in test and central control equipment as well as by using modular design.

9. As a consequence of items 6, 7, and 8 above, the number of personnel and the skill level of personnel is reduced for M-BAHN operation and maintenance. A recent study of a 6.9 mile system proposal operating 18 trains with 3 vehicles each showed the need for 150 people for M-BAHN compared to 250 to 300 for a conventional system.

10. The system operates safely. The centrally controlled safety block system prevents accidents by only having power to the secions of the track with a train on it. In addition the system design prevents possible vehicle derailment.

11. Safety for passengers is very important and is assured by: (a) passenger two-way communication from each vehicle and each station with the control center, (b) an escape path in the guideway with easy access through the front or rear door of the vehicle, (c) an inaccessible power rail (for on board consumption like light and air conditioning) only powered in the section of train location, and (d) M-BAHN facilitates elevated track and stations, largely reducing the likelihood of criminal acts (which is a big problem in subways).

12. The M-BAHN can be implemented much faster than most systems due to: (a) flexible, light construction, (b) decreased right-of-way purchase requirements, (c) standard rolled steel beams for guideway, and (d) manufactured modular components. The M-BAHN requires about half (50%) of the normal construction time, which also saves costs.

13. All of these factors and M-BAHN advantages combine to provide a high capacity, high performance and attractive transit system at significantly lower costs. Detailed study shows estimated savings of 12% on feasibility studies, 30% on construction/procurement, and 35 to 50% on operation/maintenance.

14. The M-BAHN System represents a major advancement in high technology for public transit service. Most importantly, the M-BAHN System is a reality and can be implemented immediately.

BERLIN M-BAHN

An M-BAHN System is being constructed in Berlin, West Germany, at the present time. This system is being integrated with the existing subway system in Berlin. The system will link the U-Bahn Gleisdreieck Station with the Cultural Center.

The project is being funded mainly by the German Ministry of Research and Technology. The line starts in an older subway station and will climb to an elevated structure with a portion of the line being at the surface level. The system has two tracks and three stations; one at the U-Bahn, another about midway of it's one mile length, and the other station at the Cultural Center.

To illustrate the speed of construction, the contract with Berlin was signed in 1982 and construction began in late summer 1983. It is anticipated that vehicles will be running on the line by mid 1984 for test purposes (the German government requires the system to run for a period of time before it is officially opened for public transit service).

CONCLUSION

The M-BAHN represents a major advancement in public transit advanced technology. It's many features make it a very attractive and cost effective public transit system -- one which will meet the needs of numerous communities worldwide. The M-BAHN represents new proven technology and it is a reality, ready for implementation!

The technology is here. The construction, operational, and maintenance cost savings present a dramatic advancement. The M-BAHN may be the only system which can be afforded to meet high capacity, high performance requirements. The difficulty lies not with the M-BAHN but with the local decision to proceed!

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Alternative Fuels

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DEVELOPING A CONVERSION KIT FOR THE DETROIT DIESEL ALLISON 6V-71 ENGINE TO METHANOL FUEL

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Summary

Methanol is recognized as the most attractive alternative to diesel fuel for transit bus operations. The centralized nature of operations and equipment standardization make bus transit an ideal demonstration of petroleum fuel independence. The Detroit Diesel Allison (DDA) 6V-71N engine was selected for development of a methanol conversion technology as it is the most popular transit engine. Selection of a conversion scheme from 10 candidates is summarized below, along with a description of the development of the selected conversion technique. The conversion features auto-ignition of methanol fuel which is attained by control of the scavenge air system. Starting is assisted by a glow plug installed in each combustion chamber.

PROGRAM BACKGROUND

The Florida Department of Transportation (F-DOT) is sponsoring a program to determine a method for converting existing transit buses to operate on methanol fuel. Funding for the program is provided by the State of Florida and by a grant from the U.S. Department of Transportation, Urban Mass Transportation Administration (UMTA).

The program consists of five phases: Feasibility Study; Preliminary Engineering and Coach Conversion; Service Demonstration and Evaluation; Final Engineering; and Transit Fleet Conversion Planning.

The program focus is on converting the General Motors/Detroit Diesel Allison 6V-71N Diesel-cycle transit engine. A total of four engines will be converted; three will be installed in transit buses and used in public transit demonstrations, while the fourth engine will be used for emissions and durability testing and as a program spare.

The products of the program will include technical design specifications, component conversion kit requirements, and service manuals for subsequent use by transit bus operators to convert their diesel buses to methanol fuel. Detailed fleet conversion plans will be prepared to assist transit operators and state/local authorities in making a decision to convert their transit bus fleets.

FEASIBILITY STUDY

The Phase 1 Feasibility Study was completed in February 1983 and addressed the viability of all aspects of the program. The key output of the study was identification of the engine conversion technique to be developed in the following phases. The following is a summary of the conversion options considered, and their evaluation.

Options for Converting the DDA 6V-71 Engine to Methanol Operation

Ten engine conversion techniques have been developed to operate internal combustion piston engines on methanol fuel:

Option 1--Otto Cycle/Liquid Fuel. This option considers the conversion of the DDA 6V-71 two-stroke Diesel-cycle engine to an Otto-cycle engine. The conversion requires the addition of a liquid fuel carburetor to the air intake system of the engine, a spark plug ignition system to ignite the fuel/air mixture, and new pistons to reduce the compression ratio.

The addition of a carburetor introduces throttling losses, fuel mixture distribution losses, and manifolding losses so that cold startability could be a development problem. Unvaporized fuel in the engine due to the use of a carburetor system could cause high wear rates in the cylinders and fuel economy (energy efficiency) would be very low due to the loss of fuel out the exhaust valves during the scavenging stroke.

Option 2--Otto Cycle/Vapor Fuel. This option is similar to Option 1 except that the methanol fuel is vaporized by a heat exchanger prior to mixing with air. In place of a liquid fuel carburetor is a propane-type vapor fuel mixer. The vapor fuel mixer regulates the proportion of air to fuel to allow for variations in engine speed and load. As in Option 1, a spark plug ignition system is added, along with modifications to reduce the compression ratio to approximately 12:1.

Conversion requires development of a fuel vaporization system.

Option 3--Dual Fuel/Dual Injection. This conversion option requires the addition of a second direct-injection fueling system. All other components remain unchanged. Using this method, the methanol fuel is injected in varying amounts to achieve the required power output. The original injection system supplies a small quantity of diesel fuel injected directly into the cylinder to act as an ignition source for the methanol fuel. This method requires the use of two separate fuel tanks in addition to the two separate fuel injection systems.

The major problems with this design concept are operational and included the following:

- Potential for cross-fueling the different fuel tanks
- Initial and continuing cost of two separate injection systems
- Doubling of daily fueling times
- Diminished, but continued reliance on diesel fuel.

Option 4--Dual Fuel/Fumigation. This option requires the mixing of air entering the engine with methanol prior to its entering the scavenge blower and the engine itself. Methanol is injected into the air stream by a low-pressure fuel injection system. This combustible mixture then supplies part of the energy available to perform useful work.

The greatest problem with this approach is the very small percentage of diesel fuel (20 percent) that can be replaced. Further, this system requires some development to implement the control system required to achieve even 20-percent levels of methanol use in the 6V-71 engine.

Option 5--Dual Fuel/On-Board Mixing. This option considers mixing diesel and methanol fuel on the vehicle just prior to injection in order to prevent separation of the two fuels. Modifications to the engine would include replacement of the current injectors with higher capacity units and the addition of an engine-driven mixing device.

As with Option 3, the potential problems with this approach are operational, and are associated with requiring two fuels on board the bus.

Option 6--Dual Fuel/Off-Board Mixing. This option is similar to Option 5 except that only one on-board fuel tank is used and the fuel is mixed into a semi-stable methanol/diesel emulsion prior to being put into the vehicle. Only the fuel injectors require modification.

While a theoretical maximum of 30 percent of the diesel fuel could be eliminated, it is likely that 20 percent or less could be successfully substituted using this approach. The 30 percent replacement level may not be achieved since the fuel mixture would have to be set to the value required for the most demanding condition under which the vehicle operates. The most serious developmental problem to date is the lack of a stabilizer that allows stabilized storage of the methanol/diesel emulsion for more than a few weeks.

Option 7--Cetane-Improved Fuel. This option uses fuel additives to upgrade the very low cetane rating of methanol to a level providing acceptable performance. The cetane improver is mixed with methanol prior to fueling the vehicle. Only the capacity of the fuel injection and fuel tank systems need to be increased.

The primary problem with this option is that a satisfactory cetane rating for methanol has not been attained, and indications are that when a suitable rating is attained the cost of the required additive will be high.

Option 8--Spark-Assisted Ignition. This option converts the direct-injection Diesel-cycle engine to a stratified-charge engine where fuel is injected directly into the combustion chamber and ignited by a spark plug.

The problem with converting Diesel-cycle engines to spark-assisted ignition is finding a suitable location for the spark plug in the combustion chamber, and developing a fuel injection process that delivers a combustible mixture of vaporized methanol and air to the spark plug area. This process has proven difficult with some direct-injection engines. The ignition system represents yet another problem. Even the best commercial systems are prone to electrical breakdowns within the distributor, the high tension wiring, and the spark plugs due to the high voltages required to fire spark plugs in the very high pressure combustion chamber.

Option 9--Surface-Assisted Ignition. This option relies on the heat of a surface inside the combustion chamber to both vaporize and ignite the methanol fuel shortly after injection. A glow plug installed in the combustion chamber normally provides this hot surface, particularly during cold start and warm-up. Surfaces within the combustion chamber could be suitably hot to sustain reliable ignition once the engine is warmed up.

Based on experience to date, problems with this option appear to be minor and manageable. While the glow plug could burn out, reducing the voltage on the plug as the engine warms up should eliminate the condition.

Option 10--Prechamber/Assisted Ignition. This option is a variation on Options 8 and 9, the assisted-ignition options, using an indirect-injection combustion chamber rather than an open chamber. Indirect-injection (prechamber) engines generally have lower efficiencies than direct-injection (open chamber)engines. Prechamber Diesel-cycle engines use glow plugs to assist ignition.

Placement of the glow plugs in the prechamber yields a prechamber surface-assisted ignition technique. While this technique is feasible, it has not been demonstrated in actual tests. Further, this approach, may require the nozzles of the fuel injection system to be converted from stream to spray types (typical of direct-injection engines) to provide fuel droplets small enough for reliable ignition.

Replacement of the glow plugs with spark plugs will create a prechamber spark-assisted ignition technique. Experiments with prechamber spark-assisted engines have yielded reliable ignition. Crossfiring and electrical breakdown of the ignition system are development problems, as with the open chamber spark-assisted option.

Evaluation of Options

Each of the ten conversion techniques was evaluated in the areas of convertibility, performance, emissions, operations, and cost with the DDA 6V-71 engine as the basis for comparison:

Convertibility. Evaluation of the convertibility and complexity of the conversion process resulted in the following conclusions:

- Only the Otto-cycle and prechamber options would require a piston change to modify the configuration of the combustion chamber and to change the compression ratio.
- Several of the conversion techniques required head modifications to incorporate the ignition devices (spark plugs, glow plugs, a second fuel injector, or a precombustion chamber).
- None of the conversion techniques required a change to the engine block.
- At the time, it was not known if or how much the basic engine timing would have to be changed to optimize the engine for methanol fuel.
- All of the conversion techniques requiring a fuel injection system or fuel pumps to handle methanol had a potential wear problem. The magnitude of the problem was a function of the fuel system design and the amount of methanol handled.
- All of the conversion techniques required modification to the fuel injection system. The complexity of these modifications varied with the conversion technique.
- Three conversion techniques (liquid and vapor Otto-cycles and fumigation) were not applicable to two-stroke engines due to the fuel lost in the exhaust.

Performance. Evaluation of the potential performance of each converted engine in the transit environment resulted in the following conclusions:

- The overall potential exists for power improvement; however, the desire for engine durability equal to that of the 6V-71 diesel would preclude its realization within the scope of this project.
- The potential exists for improved thermal efficiency; however, no thermal efficiency improvement was assumed.
- Low (compared to gasoline) vapor pressure and high heat of vaporization of methanol may cause unreliable cold starts.
- The vapor-fueled Otto-cycle technique is fatally flawed due to its extended time requirement for cold start.

Emissions. Environmental and emissions considerations are important, primarily for the long-term viability of the conversion. It is not possible to predict the exact emissions of the various conversions for a 6V-71 engine, as none of the techniques have been tested in this engine, and since the combustion chamber design and other intricacies of each approach have an effect on emissions.

Fueling and Operations. Evaluation of fueling and operations resulted in the following conclusions:

- Each conversion would have a different tolerance to water in the methanol fuel; therefore, this evaluation assumed the use of anhydrous neat methanol.

- All of the conversion techniques required the installation of additional fuel tank capacity on the bus.
- All of the conversion techniques required additional underground storage compatible with methanol, along with a new fueling island.
- Fumigation, on-board mixing, and off-board mixing techniques were flawed because they require more than 50 percent diesel fuel content.

Conversion and Operations Costs. Conclusions on the conversion and operations costs included:

- Capital costs were lowest using dual fuel with on-board mixing, which was eliminated in the technical evaluation.
- Operational costs were lowest using dual fuel with off-board mixing, which was also eliminated in the technical evaluation.

Fuel Cost. Evaluation of the fuel costs resulted in the following conclusions:

- The lowest fuel cost with methanol at $.70/gallon and diesel at $1/gallon was dual fuel with fumigation, which was eliminated in the technical evaluation.
- The lowest fuel cost with methanol at $.50/gallon and diesel at $1/gallon was surface-assisted ignition.
- The diesel breakeven fuel cost was $1.05/gallon, when methanol was $.50/gallon with surface-assisted ignition.

Recommendation of Surface-Assisted Ignition Option

A review of all the data revealed that only five conversion techniques, (dual-injection, cetane-improved fuel, surface-assisted ignition, spark-assisted ignition and prechamber/assisted ignition) were compatible with the program objectives. Of these, the surface-assisted ignition technique had a clear cost advantage, and should the cost of diesel fuel rise to $1.05 while the cost of methanol dropped to $0.50, the cost penalty would become zero. The technical evaluation indicated that the direct-injection surface-assisted ignition conversion technique would be the best selection and was recommended for development in Phase 2.

ENGINE CONVERSION

The engine conversion development work is being conducted along two parallel paths. The performance development is subcontracted to Detroit Diesel Allison which plans to convert the 6V-71N engine to methanol, building upon their experience in converting the 6V-92TA engine. The emissions characterization and cold start testing of the methanol engine is being conducted by the University of Santa Clara. Detroit Diesel Allison has previously demonstrated that their two-stroke engine can operate on methanol fuel by maintaining the combustion chamber temperature above 1300°F prior to injection of methanol fuel. This critical temperature is maintained at light loads and low speeds by reducing the air flow through the engine. Initial startup is obtained by the use of glow plugs installed in each combustion chamber.

The test program at DDA is a three-task effort culminating in delivery of an operational, methanol-fueled 6V-71N engine ready for installation in a transit bus along with drawings and specifications necessary to duplicate the engine. The first task, which was completed in October, required procurement and assembly of the test engine, definition and test of two conversion schemes, and selection of the best conversion scheme.

Currently, the second task is underway and requires definition of the air control system parameters for the selected conversion scheme, mechanical unit fuel injectors, and final air control system and engine configuration.

The third task requires procurement of parts and assembly of the final engine, and test and performance documentation.

The development work at the University of Santa Clara is being conducted on a 3-71 engine which is thermodynamically the same as a 6V-71N. Use of the smaller, three cylinder engine eliminates several testing variables and permits its installation in the University's cold chamber for starting tests.

Test Program

Detroit Diesel Allison was awarded a subcontract in April 1984, and by mid-July had the test cell prepared and the transit 6V-71N installed. The two conversion schemes selected for evaluation included inlet throttling both with and without exhaust throttling, and blower bypass. Since cylinder heads fitted with glow plugs were not immediately available, the engine was started and warmed up on diesel fuel before switching to methanol for testing. Screening tests were conducted at various loads at both 1200 and 2100 RPM. These tests

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analytically determined the auto-ignition limits, as shown in Figures 1 and 2.

The diesel equivalent curves included in these figures illustrate the reduced engine air consumption required to auto-ignite methanol, and that at high speeds and loads, the air consumption is similar to diesel. A comparison of efficiencies indicated that the bypass blower conversion scheme should be selected for further development in Task 2. The throttled intake performs poorly primarily because of the pumping losses resulting from the inlet restriction. The bypass blower curves are even better than the equivalent diesel curves because the bypass system reduces the power required to drive the blower. This effect is greatest at light loads due to the greater relative size of the bypass. To date, no attempt has been made to identify efficiency changes caused by the combustion of methanol fuel. At engine speeds above 1800 RPM the power level of the diesel fueled engine can be matched or exceeded with methanol fuel. At speeds below 1800 RPM the rated diesel power level has not been matched with methanol fuel, regardless of fueling level. This condition was not apparent on the turbocharged 6V-92TA methanol engine and, therefore, is thought to be combustion related. The issue is being further studied during Task 2.

At this writing the University of Santa Clara has completed the diesel baseline testing. A blower bypass system is being fabricated and the engine is being converted to methanol fuel.

Technical Issues

Engine operation on methanol fuel has revealed a number of technical issues to be resolved before the first 6V-71N is ready for installation in a transit bus.

Heads. A substantial effort is being made to install glow plugs into the original cylinder heads as new head castings would greatly increase engine conversion costs. A set of heads have been modified, as shown in Figure 3, to accept production glow plugs. This modification involved only machined hardware as past experience with brazed and welded head modifications has been unsatisfactory. The diametrical clearance between the glow plug body and the pass-through sleeve of .225 inches was recommended by AC Spark Plug, the glow plug manufacturer. This clearance proved inadequate as the plugs failed to attain sufficient temperature to allow room temperature engine starts on methanol. The glow plug clearance hole was enlarged providing a new clearance of .312 inches, which permitted successful cold engine starts on methanol fuel. However, re-boring the original sleeves weakened the sleeve in the thread area resulting in the loss of retention torque and barking out of the sleeves. The heads were remachined with an enlarged (14 mm) thread and new larger sleeves were manufactured. The new sleeves have a .312 clearance to the glow plug and are to date performing satisfactorily.

As a contingency measure, Detroit Diesel Allison has procured head castings with a cast in boss for glow plug installation. These heads will be used on the final engine only if the machine modified heads prove unsatisfactory.

Fuel Injectors. All engine development operations on methanol fuel have been conducted with high capacity, unit-type fuel injectors. A limited number of these injectors were tool room manufactured, by Rochester Products, for this program. They have a rated capacity of $200\ mm^3$, which is more than three times the capacity of the standard transit 6V-71N diesel fuel injectors. These injectors apparently have a minor dimensional or metallurgical problem as five suffered failure by seizure of the bushing and plunger. If one injector had not failed while being run-in on diesel fuel, the poor lubricity of methanol would have been blamed for the subsequent failures. A large quantity of $200mm^3$ fuel injectors have subsequently been produced on production tools, and are planned for use in the final engines.

Four unexplained failures of the engine driven fuel pump were also experienced during developmental testing. This pump will not be necessary in the methanol bus installation as an electric driven pump mounted near the tank will pressurize the engine fuel system. This approach not only allows elimination of the engine driven fuel pump but reduces the likelihood of vapor lock due to fuel boiling in the lines.

Aldehydes. Aldehydes in general, and formaldehyde in particular, are the major pollutants generated by methanol-fueled engines. At the present time aldehyde emissions are not regulated, however, they certainly will be subjected to regulation when methanol becomes popular as a motor fuel. The University of Santa Clara is responsible for measuring aldehydes along with other gaseous emissions generated by the methanol-fueled 6V-71N engines during this program.

A subjective evaluation of a transit bus fitted with a methanol-fueled 6V-92TA concluded that the odor generated by the aldehyde emissions are unacceptable for public exposure. To preclude the possibility of this odor condition occuring on the 6V-71N engines during the revenue service demonstration, the efforts of the University of Santa Clara have been redirected toward control of aldehyde emissions. These emissions have been

71 N METHANOL

1200 RPM CR= 19 BOI= 16 BTDC

AUTOIGNITION LIMIT

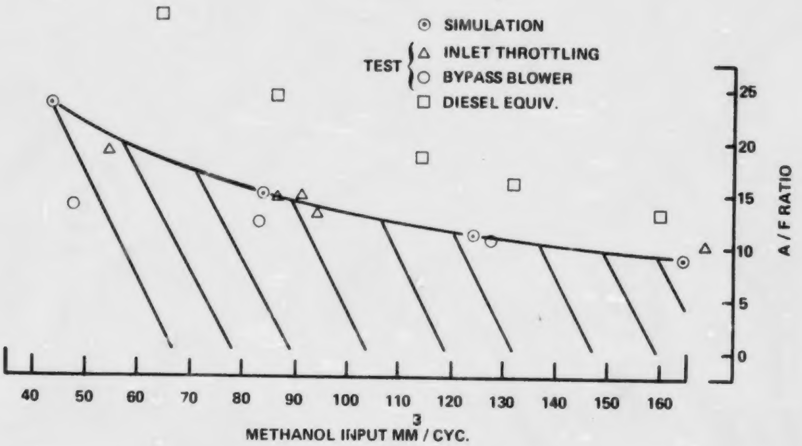

Figure 1. Auto-Ignition Limits (1200 RPM)

71 N METHANOL

2100 RPM CR= 19 BOI= 16 BTDC

AUTOIGNITION LIMIT

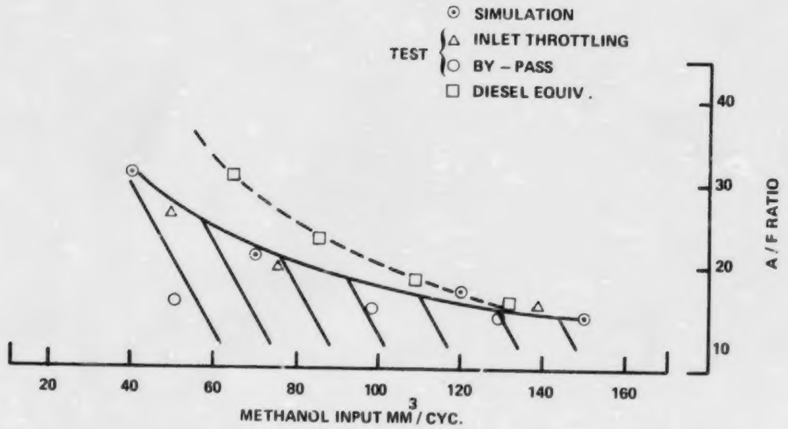

Figure 2. Auto-Ignition Limits (2100 RPM)

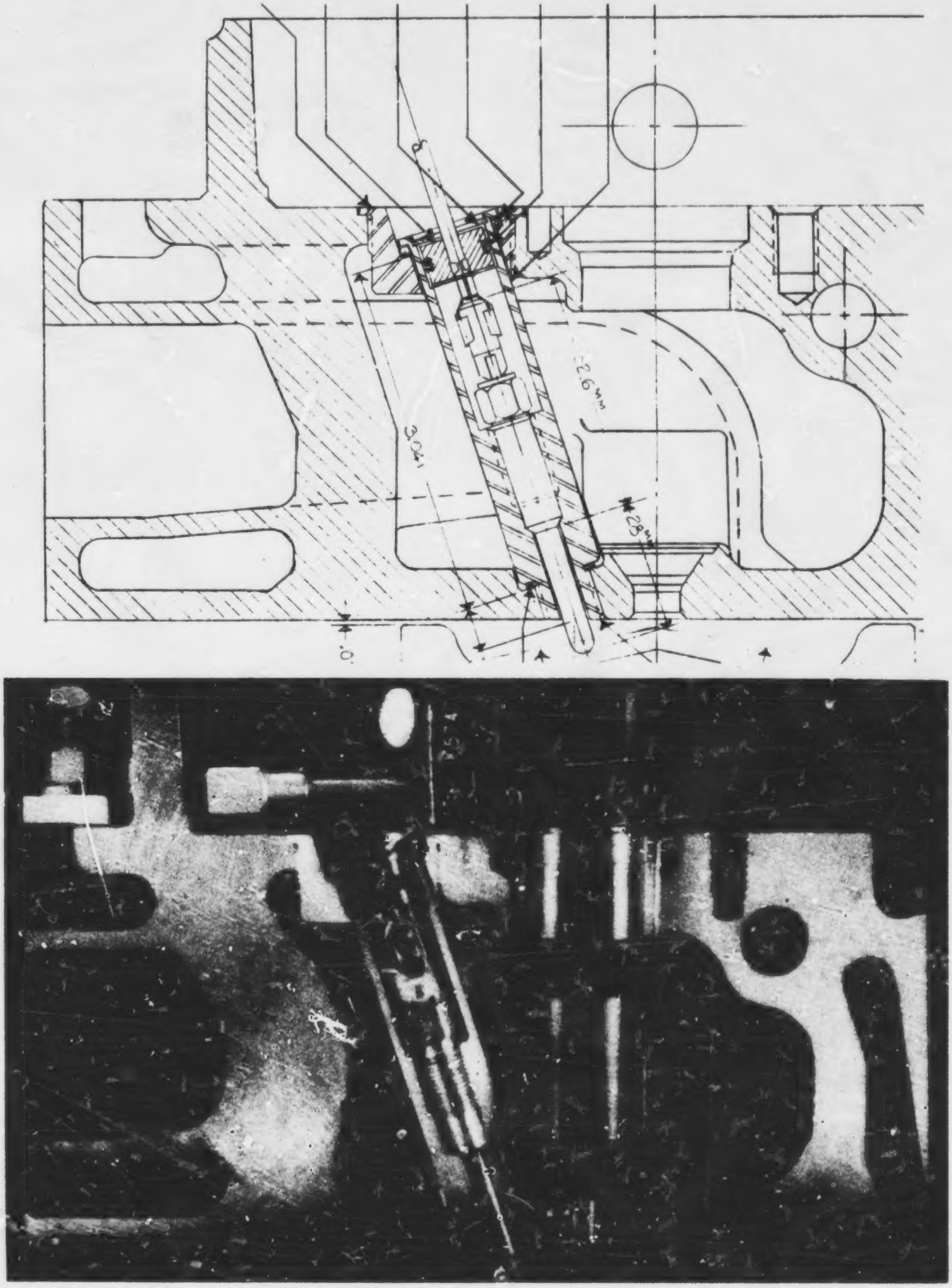
22.6mm
30.21
28mm
0

Figure 3. Head Modifications

successfully controlled on Otto-cycle engines with an oxidizing catalytic converter. The low temperature of exhaust gases of a Diesel-cycle engine at low speeds and loads could prevent the catalytic converter from reaching its critical "light-off" temperature. Should the converter not attain this temperature, the aldehyde emissions could be increased as the cold catalyst may convert unburned methanol in the exhaust to aldehydes.

Engelhard Industries has been asked to assist with the development of a proper catalytic converter protocol for the 6V-71N engine. Preliminary work indicates that developing a proper system is feasible. Since the air consumption of the methanol converted Diesel-cycle engine is reduced, the exhaust gas temperature is raised. Small "light-off" catalytic converters, with low thermal inertias, located at the exhaust manifold outlets are expected to effectively reduce aldehyde emissions during idle and light load operation. Their small size should allow them to light off quickly after start-up. A full sized catalytic converter locatd near the coach muffler will handle aldehyde emissions at high engine speeds and loads when the light-off units have insufficient capacity. The light-off catalysts heat the exhaust gases sufficiently to maintain the critical temperature in the full sized unit after warm-up.

Heavy duty engine oils (rated CD) are required in Detroit Diesel Allison engines for their lubricating and film strength properties. These oils typically contain .11-.15 mass percent of phosphorus. This concentration of phosphorus will poison the catalytic converter when introduced by normal consumption of lube oil past the piston rings. A Voil or Boron-based fuel additive is being investigated to offset phosphorus poisoning of the catalytic substrate.

Air control. The final technical issue to be reached is development of the control system to manage the air flow into the engine. The air requirements are just now being defined, therefore, design of the control system is premature. The control system must be both engine speed and load sensitive and may have special functions for engine idle with air conditioning on. A mechanical system approach is planned to reduce conversion costs.

CONCLUSIONS

Experience to date indicates that the Detroit Diesel Allison 6V-71N engine can be economically converted to operate on methanol fuel. This conversion technique, when finally developed and demonstrated, will give public transit authorities the ability to implement effective contingency strategies against future diesel fuel supply disruptions or unnatural escalations in diesel fuel price. In addition, the operating transit cost could be reduced by capitalizing on the anticipated long term surplus of methanol. Implementation of these strategies may begin as early as 1985.

A PRELIMINARY ASSESSMENT OF NATURAL-GAS-FUELED URBAN BUS FLEETS

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INTRODUCTION

Over the past 10 years, a considerable amount of research has been directed toward the development and use of alternative fuels. While much of this research sought to develop crudes for the production of petroleum fuel look-alikes, advances were also made in the use of non-petroleum type fuels such as methanol, natural gas, and hydrogen. Of these alternatives, natural gas is the only domestic fuel available today in sufficient quantities to meet transit bus needs.

This paper reviews the technology status of natural gas for vehicle applications, examines the economics of natural gas for transit coach use, and presents a brief argument for the development of natural gas transit coaches.

ENGINE CONVERSIONS

The conversion of normally aspirated gasoline 4-cycle engines to operate on natural gas is routinely performed in a few hours using off-the-shelf equipment from one of several manufacturers (both domestic and international). The conversion allows 100% natural gas operation and generally provide for a switch back to gasoline operation via a dash-mounted switch.

Four-cycle diesel engines may be converted to high compression, spark-ignited natural gas engines. This practice is common in industrial applications. Both Catapillar and Cummins, for example, offer conversion components for several of their engines. For vehicle applications, the approach being pursued by the conversion kit developers is that of pilot diesel injection. With this approach, natural gas is inducted into the engine via the intake valve and ignited once compressed by a small quantity of diesel fuel, which is injected in the normal manner.

The amount of diesel fuel displaced using this approach ranges from zero at no-load to about 80% under full-load conditions. The diesel fuel displacement realized under normal vehicle-use conditions will depend upon the vehicle-use pattern.

Conversion kits for 2-stroke diesel engines which employ blown intake air to scavenge the cylinder, such as the DDA coach engine, have not yet been developed for vehicle applications. Industrial 100%- natural-gas- and pilot-diesel-based conversions do exist, and vehicle systems are being considered.

Costs range from $400 for gasoline engine under-hood components to $1000 for 4-cycle diesel kits. Installation labor costs are estimated at 50% of hardware costs. Recent estimates for a 2-cycle retrofit diesel conversion kit are $2000 for an installed kit, once developed.

ONBOARD FUEL STORAGE

The most common method of storing natural gas onboard a vehicle is in DOT-certified cylinders at pressures up to 3000 psi. Some vehicles have utilized liquefied natural gas (LNG) but the technology is not as widespread as compressed natural gas due to availability of LNG and, in some cases, restrictions and regulations. Research and development efforts are underway to utilize adsorbant materials to lower required pressures, but this technology is not commercialized yet. Accordingly, this paper considers only the use of compressed natural gas.

A coach with a desired range between refuelings of 300 miles requires approximately 70-80 gallons of diesel fuel or its equivalent in natural gas. Table 1 shows the fuel storage requirements for various percentages of natural gas/diesel substitution, based on an 80-gallon baseline requirement.

For a vehicle able to substitute 50% natural gas, sufficient space exists for the cylinders (without disturbing the diesel tank) under both the 40-foot GM RTS and ADB coaches. For vehicles able to achieve higher substitution rates, installation of a smaller diesel tank should allow sufficient space for additional cylinders. For a dedicated natural gas vehicle, the entire diesel tank can be removed. Alternatively, new RTS coaches can be ordered with a passenger module replacing the fuel tank module. Coaches less than 40-feet in length have not been explicitly studied. In the 35-foot GM RTS coach, it is possible to add cylinders to the air tank module, although care must be taken to permit service access to all components.

A dedicated natural gas vehicle would require $6738 in onboard tank costs. The full storage would weigh 2740 pounds compared with approximately 670 pounds for a full diesel tank. At 50% substitution, the vehicle would require $3369 in onboard tank costs. With a normal full diesel tank, added weight with full natural gas storage is about 1370 pounds.

Table 1. FUEL STORAGE REQUIREMENTS VS. PERCENT NATURAL GAS USED

Natural Gas Use, %	Fuel Mix		Cylinder Weight, #	Cylinder Cost, $	Fuel Weight	
	Diesel, Gal.	Nat. Gas, SCF			Diesel, #	Nat. Gas, #
0	80.00	0	0	0	570	0
5	76.00	584	112	337	541	25
10	72.00	1168	225	674	513	49
15	68.00	1752	337	1011	484	74
20	64.00	2336	449	1348	456	99
25	60.00	2920	562	1685	427	124
30	56.00	3504	674	2022	399	148
35	52.00	4088	786	2358	370	173
40	48.00	4672	898	2695	342	198
45	44.00	5256	1011	3032	313	222
50	40.00	5840	1123	3369	285	247
55	36.00	6424	1235	3706	256	272
60	32.00	7008	1348	4043	228	296
65	28.00	7592	1460	4380	199	321
70	24.00	8176	1572	4717	171	346
75	20.00	8760	1685	5054	142	371
80	16.00	9344	1797	5391	114	395
85	12.00	9928	1909	5728	85	420
90	8.00	10512	2022	6065	57	445
95	4.00	11096	2134	6402	28	469
100	0.00	11680	2246	6738	0	494

Table 1 has been constructed assuming the use of composite aluminum fiberglass cylinders. The use of steel cylinders would reduce costs by about 40% while doubling cylinder weight.

REFUELING SYSTEMS

Natural gas is generally available at pressures from a few psig to approximately 50 psig in industrial areas. A compressor is required to raise the pressure to at least the onboard storage pressure used on the vehicle.

Two systems of refueling are in use in the U.S.: "quick" and "slow" fill. Quick fill is similar to conventional liquid fuel refueling. A vehicle is moved to the refueling area, a high pressure connection is made, and refueling occurs in a matter of minutes. Slow fill is used for vehicles which are out-of-service for extended periods, e.g., overnight. Here, many vehicles are connected to refueling lines for 6-12 hours. Initial capital costs for the two options are not much different, and the choice of which to use (including a hybrid) is made based on operational logistical input.

Large capacity stations are typically made up of several identical compressors to allow operation to go on while necessary routine compressor maintenance is being performed.

Compressors capable of providing the equivalent of 1000 gallons of diesel fuel in a 12-hour period cost approximately $100,000. Auxiliary gas storage to make this a quick-fill station costs about $20,000. Piping and hardware necessary to make 20 slow-fill stations also costs about $20,000. Approximately $10,000 is required for an outside roof, support concrete slab, and utility service routing.

Compression costs are approximately $.12 per equivalent gallon of diesel fuel, $.02 for compressor maintenance, and the balance for electrical power to operate the unit.

OPERATIONAL IMPACTS

The major operational impacts of natural gas as a fuel relating to a transit system's economics are refueling-related. Current natural gas refueling systems transfer fuel at the rate of 1-2 gallons per minute per refueling nozzle, and are limited in their total fuel flow rate capacity. This feature will likely lengthen refueling times and impact bus cleaning and refueling schedules. This limitation may be particularly noticable in systems where the coaches are serviced during an evening shift for next-day duty. In these applications, an overnight time-fill system will most likely be required.

This slower fuel transfer rate could also limit the potential of dispersed refueling systems for in-route vehicle refueling. This practice, if implemented, could reduce the onboard fuel containment system cost by about 50%. Staffing needs and route schedule impacts nessary to accomodate this practice will need to be thoroughly examined.

One important aspect of the pilot ignition, dual fuel mode of engine operation is the ability to switch back to 100% diesel operation. On coaches where insufficient space for natural gas storage exists for all-day operation, this allows two options. The first is to alter schedules to permit mid-day natural gas refueling either by bringing the vehicle back to the central refueling site or by providing satellite refueling stations at points in common to several routes (transfer points). Alternatively, one could simply use up the natural gas onboard and finish the day on diesel. The latter would lose some of the savings inherent in natural gas utilization but minimize operational impacts.

ECONOMICS

A representative fleet, consisting of 160 coaches, has been analyzed for economic benefit. Table 2 shows the operating details of the fleet. The ratio of in-use coaches to those in reserve and awaiting repair was derived from discussions with both large and small transit companies. Once and twice per day, refueling was considered for 25%, 50%, 75%, and 100% natural gas substitution for diesel fuel. Fuel price differentials at the vehicle of $.10, $.20, and $.30 per gallon were considered.

Table 2. REPRESENTATIVE FLEET FOR ECONOMIC ANALYSIS

Coaches	
In-Use Peak Hours:	112
Stand-By Reserve:	16
Running Repairs:	16
Down for Service:	16
Total Coaches:	160
Total Fuel Use (gal/day):	5,700
Coach Use (miles/day):	180-240
Max. Use Service Day:	6:30 AM-10:00 PM

Table 3 shows the details for 100% substitution with twice/day refueling, and Table 4 shows the simple payback times in years for all options considered. Note that for fuel differentials (savings) of $.20/gallon or more, and for at least 50% natural gas substitution, the results are quite favorable. All cases show net operational savings, yielding finite payback times.

At this writing, the realizable differential is only about $.15/gallon. This is, however, the least favorable natural gas-diesel differential that has existed in the recent past. Projections indicate that higher differentials are likely to occur in the future.

CONCLUDING REMARKS

A quick review of urban transit coach conversion to at least partial natural gas operation has been provided. For realizable fuel price differentials, economics alone will not provide the driving motivation.

In times of crisis, e.g., a mideast war, crude oil supplies may be interrupted. Urban transit fleets will have to compete with trucking, air travel, and home heating for their share of the middle distillate fraction of available oil supply.

Steps to operate urban transit on a secure domestic fuel can be taken now to minimize impacts of future fuel crises, while slightly lowering operating costs in the meantime.

Table 3. DETAILED CALCULATIONS FOR 100 % NG USE, 2 REFUELING PER VEHICLE PER DAY

Description	Amount	1000$
Refuelings/Day	2	
NG Used, Percent	100	
Vehicles	160	
Fuel Storage Costs/Veh.		6.738
Engine Conversion Cost/Veh.		2
Daily Fuel Usage, Gal.	5,700	
Operating Days/Year	300	
No. of Refueling Compress.	4	
Cost/Compressor & Station		130
------- TOTAL FLEET ------		
Total Onboard Storage Costs		539.04
Total Engine Conversion Costs		320
Total Station Costs		520
Total Conversion Costs		1,379.04
Total Diesel Displaced (gallons/year)		1.71 X 10^6
...Savings at $.10/gallon..........		171,000
...Savings at $.20/gallon..........		342,000
...Savings at $.30/gallon..........		513,000
...Simple Payback at $.10/gallon...		8.06 years
...Simple Payback at $.20/gallon...		4.03 years
...Simple Payback at $.30/gallon...		2.69 years

Table 4. SIMPLE PAYBACK FOR NATURAL GAS USE HAVING DIFFERENT PERCENTAGES AND REFUELING SCHEDULES

# Refuelings/Day	Natural Gas Use, %	Simple Payback in Years With		
		$.10/gal savings	$.20/gal savings	$.30/gal savings
1	.25	18.35	9.18	6.12
1	.50	14.61	7.30	4.87
1	.75	13.36	6.68	4.45
1	1.00	12.74	6.37	4.25
2	.25	13.68	6.84	4.56
2	.50	9.94	4.97	3.31
2	.75	8.69	4.34	2.90
2	1.00	8.06	4.03	2.69

EVALUATION OF ALTERNATIVE FUELS FOR URBAN MASS TRANSIT BUSES

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INTRODUCTION

The well known "oil crises" of the early and late 1970s have sparked great concern among private industry, government and individuals about the sensitivity of our economy to imported oil. Oil prices rose so high during the 1970s that fuel conservation efforts, in the public and private sectors, became a priority. Economics combined with the potential threat of future fuelsupply interuptions made the use of alternative energy sources a viable approach to reducing the United States' dependence on foreign oil.

Our most recognized need for oil is for transportation - transporting raw materials to factories, finished goods to distribution centers and individuals to work. However because of our dependence, foreign oil has gained tremendous leverage on transportation costs and our ability to provide adequate transportation.

Public transit plays a key role in the transportation needs of the United States, not only in routine movement of people, but also in the increased demand during crises such as past oil shortages. Public transportation must remain an economically viable and reliable people mover.

To help prepare the transit industry for potentially damaging trends or sudden changes in oil price and/or supply, the Port Authority of Allegheny County commissioned a study to identify an alternative to diesel fuel for transit buses. The study was financed through a grant from the United States Department of Transportation, Urban Mass Transportation Administration.

Our study to identify an alternative fuel for the Port Authority of Allegheny County encompassed:

- A preliminary screen--an evaluation of all known gaseous and liquid fuels to identify candidates for further study
- A secondary screen--a detailed analysis of six candidate fuels
- The alternative fuel selection.

We determined methanol to be the best alternative fuel for transit bus operations. Methanol use involves a relatively low initial cost, low technical risks, offers the flexibility of converting back to diesel relatively easily, and is not petroleum based.

PRELIMINARY SCREEN

The purpose of the preliminary screen stage of the study was to narrow the very wide range of alternative fuels to the six most practical candidates for more detailed analyses. We began with an extensive literature search for fuels that had been or could be used in internal combustion engines. Next, we developed a ranking criteria for the fuels. We then used the criteria to select fuels for further study. Each of these steps is described below.

Literature Search

The literature search uncovered over 300 relevant titles, representing close to 1,000 individual research and demonstration projects involving alternative fuels. Most of these projects have taken place in the last four years and are devoted primarily to alcohol fuels. Of the 40 potential alternative fuels identified in the literature search and listed in Exhibit 1, at least 22 have been used in internal combustion engine research, development, or test projects.

Since the study objective was to select an alternative to diesel, a petroluem-based fuel, the list of potential fuels was reduced to include only fuels that are not produced directly from crude oil. This reduced fuels list is shown in Exhibit 2.

Ranking Criteria

Criteria for ranking the fuels were developed for each of the following categories:

- Cost
- Availability
- Technical feasibility in a diesel engine
- Safety in transit operations
- Operational impacts on the transit system
- Institutional factors that may limit fuel use.

Whereas the segmentation of each rating category was clear cut, the actual positioning of each fuel within a particular segment of a category was based on professional juagement as well as on interpretation of the available literature. It should also be noted that the standard for each comparison was diesel fuel, the current fuel used for transit bus operations in the United States.

The technology changes anticipated to occur over time were also taken into account by ranking the fuels in reference to three

Petroleum
  - Gasoline
  - Naphtha
  - Kerosene
  - Heavy Oils
  - Reprocessed Drail Oil
  - Diesel

Synthetic Fuels
  - Coal Tar
  - Shale Oil
  - Colloidial (Coal in Oil)
  - Hydrogenated Coal
  - Fischer-Tropsch
  - SCR-II

Aromatics:
  - Benzene
  - Tolune
  - Xylene

Alcohols:
  - Methanol
  - Ethanol
  - Isoproanol
  - Tertiary Butanol

Paraffins:
  - Methane
  - Ethane
  - Propane
  - Butane
  - Pentane
  - Hexane
  - Heptane

Solids:
  - Coal (Pulverized)
  - Naphthalene
  - Peat
  - Bagasse

Olefins:
  - Ethylene
  - Propylene
  - Butylene

Misc. Organic Liquids
  - Acetic Acid
  - Nitromethane
  - Vegetable Oils

Gaseous Fuels:
  - Ammonia
  - Coal Gas
  - Carbon Monoxide
  - Hydrogen

Exhibit 1. Alternate Fuels

Synthetic Fuels
  - Coal Tar
  - Shale Oil
  - Colloidial (Coal in Oil)
  - Hydrogenated Coal
  - Fischer-Tropsch
  - SCR-II

Alcohols:
  - Methanol
  - Ethanol

Paraffins:
  - Methane
  - Propane

Solids:
  - Coal (Pulverized)

Gaseous Fuels:
  - Ammonia
  - Coal Gas
  - Carbon Monoxide
  - Hydrogen

Exhibit 2. Non-Import-Based Alternate Fuels

different time frames. The ranking was performed on a near-term (1983-1985), inter-mediate-term (1985-1995), and long-term (1995-2010) basis.

Once again, it is important to note that the available literature and the experience of the research staff both played a part in the preliminary screen ranking of the fuels. The subjectiveness of the methodology used during this initial screen is reflected in the qualitative (i.e., best, very good, good) presentation of the fuels recommended for detailed study.

Selection of Fuels for Further Study

From the preliminary screen fuels list, ammonia, ethanol, hydrogen, methane (natural gas), methanol, and propane were selected to be studied in detail. Each of these fuels could be derived from either natural gas or coal through a coal gasification process and therefore could make the transit industry independent from imported crude oil. Only propane is imported in significant quantities at this time (about one-third of U.S. consumption) but this is primarily a function of selling price.

The fuels not selected for further study generally suffered from supply-related uncertainties. Only coal was considered to have the capability of being available in large quantities in the future, but it will primarily be used as as feedstock in the production of other more portable and technically feasible fuels for direct use in diesel engines. The six fuels selected for further study are discussed in the next section.

SECONDARY SCREEN

The secondary screen examined the six fuels selected above in much more detail. Areas covered included fuel cost and availability, technical feasibility of each fuel in a diesel engine, fuel handling and safety, life cycle costs, and risk associated with each fuel.

Fuel Costs and Availability

The best place to begin a discussion of future price estimates for the six alternative fuels is at their source since both the costs of the source material and the fuel production costs figure into the final product price. The six fuels presented in this study can be derived from five primary sources: crude oil, natural gas, coal, water, and biomass.

Crude oil is the major source of current transportation fuels. The next source of transportation fuels is natural gas. Since natural gas (94.9 percent methane) is currently used in only 20,000 vehicles, its use as a transportation fuel in the United States is miniscule. Use of the other fuel sources-- coal, water, biomass--is nonexistent, except for a few experimental vehicles.

The fuel price forecasts shown in this section are retail price forecasts excluding excise or other transportation taxes. Each price forecast is separated into a high, moderate and low price case. The high case is a forecast of expected prices which could occur if major political events create a supply cut-off of crude oil. The moderate case is considered to be the most likely progression of each fuel's price. The low case represents fuel prices which could result from world over-supply or new energy production breakthrough. Energy price projections were developed by Booz, Allen to bracket future events. The projections are not infallible. If future events cause even larger variations in fuel prices, the report conclusions must be reevaluated.

Methane (Natural Gas). The terms methane and natural gas are used as synonyms since methane is the primary component of natural gas, which is often used in its unprocessed form as a transporation fuel. The exact composition of methane fuel may vary due to basic inground gas differences and the degree of processing used (the amount of non-methane hydrocarbons removed).

Methane gas price trends will be highly dependent on political and economic pressures. The U.S. Congress has enacted the Natural Gas Price Act (NGPA) to begin deregulation of natural gas prices in 1985. As a result of deregulation, gas prices can be expected to rise faster than crude oil prices. Exhibit 3 presents three possible scenarios for methane prices. The low case assumes that current deregulation legislation will be rescinded and that methane prices will rise slowly. The moderate case assumes that a phased deregulation will occur that allows prices to rise in the near term and that most methane will be deregulated by 1988. The high case assumes that there is early deregulation of methane coupled with a "windfall profits" tax and that all methane will be deregulated by 1986. (We similarly developed three scenarios for the other fuels, however they are not illustrated in this paper.)

Even with complete deregulation, the ultimate price of methane is expected to level out in constant dollar terms. This assumption is based on interviews with industry officials who believe that the U.S. has a tremendous reserve of natural gas at a price above $5/per million (MM) Btu at the wellhead.

Methane is also the primary feedstock for ammonia, methanol and some propane. Therefore, the prices of these fuels are all directly dependent on the price of methane. It is also possible to produce hydrocarbon gases from coal and then upgrade these gases through a number of synthetic processes to produce methanol, methane, and ammonia. But there are currently no large-scale coal to coal-gas plants in the United States since it is cheaper to use methane as a feedstock.

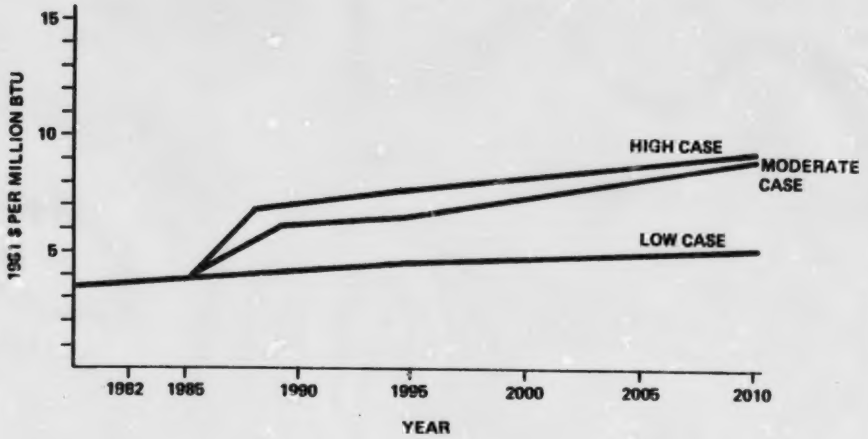

Exhibit 3. Methane Price Forecasts

Ammonia. Ammonia is produced by a catalytic reaction of hydrocarbons from natural gas and air (nitrogen). Ammonia prices will be completely dependent on natural gas prices. The low, moderate, and high case scenarios exactly follow the trends of projected natural gas prices with an ammonia production cost factor added. Ammonia produced from coal is not expected to be cost competitive during the time period investigated.

Hydrogen. Hydrogen may be derived from methane, coal, or water (through electrolysis). Presently, the only technology suitable for producing hydrogen in sufficient quantities for transit use is by electrolysis. The Natural Research Council concluded that liquid hydrogen by electrolysis would cost about $24/MM Btu. From coal, it could be produced for $13.90/MM Btu and from methane for $11.30/MM Btu (in 1979 dollars).

The price scenarios were based on the production of hydrogen by electrolysis in the near-term and from coal or methane in the intermediate-and long-terms. Each case was based on electricity costs in the near-term and methane costs in the intermediate-and long-term.

Ethanol. Anhydrous (200 proof) ethanol can be produced through fermentation and distillation of grains, sugars, and other biomass waste. Ethanol has been sold as a 90 percent gasoline and 10 percent ethanol blend called "gasohol". Capacity for ethanol production in the United States is around 200,000 gallons of neat ethanol per day (about 5 percent of the amount that would be required for the U.S. transit bus fleet).The price of ethanol is not expected to vary with time since the biomass feederstocks (grains, sugars and wood) are expected to hold their current price relationship in constant dollars in the future. There are no new process technologies known at this time that could change the production cost picture. Therefore, ethanol prices are projected to remain high and constant in time.

Methanol. Approximately two-thirds of the methanol produced in the United States (1.4 billion gallons in 1980) goes into the manufacture of chemicals and nearly half of it is oxidized to make formaldehyde for use in the pharmaceutical industry. It is used in the production and refining of petroleum, and has been used as a racing fuel since the 1930s. Considering the quantity of methanol produced, however, its use as a transportation fuel is insignificant. The current production of methanol in the United States could supply about 66 percent of the U.S. transit bus fleet.

Currently, methanol is derived from the reaction of carbon monoxide with hydrogen. Natural gas is the feedstock for this process. Gasified coal can also be used to produce methanol. But the synthetic production of methanol from coal on a commercial scale is not economical at the present time. Since it takes from 7 to 10 years to build a large-scale coal to liquid-fuel facility, it is not likely that methanol will be produced from coal in the United States in the near or imtermediate term.

Methanol produced from natural gas would probably always be less expensive than methanol made from U.S. coal since the price of natural gas is expected to stabilize, causing an oversupply for the foreseeable future. Furthermore, imported methanol produced from remote gas supplies could keep prices stable indefinitely. As was the case for ammonia, the future price projections for methanol follow the price expectations for natural gas, plus production costs.

Propane. Propane is processed by "stripping" natural gas or as a by-product of crude oil refining. It is currently used by the transportation industry as an alternative fuel in Otto cycle (gasoline-type) engines. The transportation industry uses about 880 million gallons of liquified propane a year. This is about equal to the supply required for the entire transit bus fleet.

Propane prices are expected to follow the trend in crude oil prices. Since propane can be processed from natural gas in addition to crude oil, though, it is expected to maintain a slight price advantage over diesel fuel in the long term.

Technical Feasibility in a Diesel Engine

Alternative fuels cannot be used directly in a diesel engine; appropriate conversions of the engine are necessary for adequate combustion of non-diesel fuels. A number of standard diesel transit coach engines have been redesigned for use with alternative fuels and have already been tested. For example Daimler-Benz and M.A.N. have developed successful conversions that run on methanol.

To determine the technical feasibility of the six alternative fuels in a diesel engine, conversion options had to be identified, options evaluated, and the most viable fuel/conversion option combination selected. These evaluation steps are discussed in the following paragraphs.

Identification of Engine Conversion Options. A number of engine conversion approaches (options) have been developed to operate internal combustion piston engines with diesel-alternative fuels (mostly alcohol fuels). These include:

- Option 1 Otto Cycle--This option involves the conversion of the diesel cycle to an Otto cycle. The conversion would require the addition of a liquid fuel carburetor to the air intake system to fuel the engine. A spark plug ignition system would be required to ignite the fuel/air mixture.
- Option 2 Dual Injection, Dual Fuel-- This conversion option requires the addition of another direct injection fueling system to the engine. All other components would remain unchanged.
- Option 3 Fumigation, Dual Fuel--This option requires the mixing of the air entering the engine with the alternative fuel prior to entering the engine itself.
- Option 4 Assisted Ignition--This option converts the diesel to a stratfied-charged engine type where fuel is injected directly into the combustion chamber and ignited by a spark plug or glow plug.

Evaluation of Engine Conversion Options. Each of the diesel engine technology approaches was evaluated for their impact on performance, fueling and transit operations.

The major performance evaluation factors were in the area of engine performance and cold startability. The conclusions were:

- All technologies will probably result in equal or lower thermal efficiency
- High (compared to gasoline) heat of vaporization of liquid fuels may cause unreliable cold starts
- Power and torque can probably be made to equal diesel performance in all options.

In the area of fueling, two of the engine options are unable to provide 100 percent diesel replacement by an alternative fuel. These options are dual fuel injection and fumigated fuel. These approaches are not considered acceptable, since substitution of less than 100 pecent of diesel fuel does not serve transit's goals of reducing its dependence on petroleum-based fuel operation. Other considerations arise which make dual fuel operations more difficult than single fuels. Fuel storage and handling becomes more complicated both on-site and on the vehicle. The probability that the wrong fuel could be placed in the wrong tank is very high if both fuels are liquids. If different safety procedures are needed for each fuel, then the possibility arises that unsafe habits could develop, because of the human tendency to treat similary types of fuels in the same manner.

Impacting transit operations, all of the conversion approaches require the installation of additional or severely modified fuel tank capacity on the bus. All of the approaches require specialized fuel storage.

Of the four possible engine conversion approaches, only one was found to be feasible for further consideration: assisted ignition. This type of engine can accept fuels which exhibit either good compression ignition characteristics or good spark ignition characteristics. The M.A.N. D 2566 FMUH is an example of this type of engine. It is capable of running on a variety of fuels.

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An evaluation of the resultant six alternative fuel/diesel engine conversions combinations was performed. Only methanol and ethanol are currently viable for use in assisted ignition diesel engines. The remaining fuel/engine conversion combinations may be viable but research to date shows that many development problems remain to be solved.

The liquid state of methanol and ethanol makes them suitable for injection into the combustion chamber of assisted ignition diesel engines. Some research has shown that propane and ammonia may be directly injected in liquid form, but there are currently no known gaseous fuel injection systems. It is not known this time whether gaseous fuels are viable for use in the assisted ignition diesel engine. Even if a technique is found to successfully inject gaseous fuels into the cylinder, there may still be a problem with premature ignition. There is some technical risk and much development required before gases, such as hydrogen and methane, may be usable in a diesel engine with direct injection.

In conclusion, an examination of the engine technology found that the liquid fuels are most viable for application in the available diesel engine conversion approaches. Currently, there are no injection pumps available for directly injecting gaseous fuels, although their development is possible and consideration will be given to gaseous alternatively-fueled diesel engines later.

Fuel Handling and Safety

Diesel fuel is one of the safest and easiest to use of the available fuels. Also diesel fuel storage, handling, and transportation are comparatively simple and inexpensive, even compared to other petroleum fuels.

The use of alternative fuels in transit operations raises safety, operations, and institutional issues that must be considered along with the economic and technical issues. These issues are most easily discussed when the fuels are grouped according to their physical properties as a liquid, a heavy gas, or a light gas.

Liquids. Ethanol and methanol are liquids at room temperature. The primary concern in using them in the transit industry is not the lack of experience or knowledge about their properties, but the effective training and control of the personnel who will be exposed to them for the first time. New safety habits must be developed, knowledge of the new fueling techniques must be taught, and management must install controls to ensure that safety procedures are followed.

Heavy Gases. Propane and ammonia are gases at room temperature and standard pressure, but they can be stored as a liquid at moderate pressures (100-200 PSI). The primary consideration in using heavy gaseous fuels is the training of personnel and the firm establishment of good safety habits.

Ammonia is very toxic but is very easily detected by the human olfactory system. Fueling times will be the same or slightly longer depending on the capacity of the pumping equipment. Fueling must take place in an open area. This could alter some operational procedures at most transit properties but it should not be signifiant enough to preclude the use of these fuels.

Propane is already used by many fleet operators around the United States and special above ground tanks are used to store the fuel. While individual state regulations vary, the National Fire Protection Association issues fuel dispensing and storage requirements. Propane is heavier than air and can settle into a gaseous "puddle" if there is no air movement to disperse it. Propane has very narrow flammability limits and is not as likely to ignite as gasoline. However, the heavier than air characteristic of propane and its potential for developing an explosive mixture in enclosed spaces can make it highly dangerous if improperly used.

Light gases. Methane and hydrogen are lighter than air (hydrogen is the lightest element). Both are gases at high pressures (2400 PSI) and room temperatures (70°F), but can be stored as liquids at very cold temperatures. Methane can be stored as a liquid at -260°F and hydrogen at -423°F. Whether stored as gases or liquids, methane and hydrogen require very specialized and expensive storage systems.

Since the energy content of gaseous fuels is very low on a volume basis (Btu's per SCF), they must be compressed or liquefied to save storage space within the vehicle and to meet the transit bus range of about 100 miles per shift. The machinery required to liquify methane and hydrogen is complex and costly, therefore it is likely that they would be trucked in as liquid fuel.

Much work must be done on the production, handling, transportation, and storage systems required to support hydrogen use (liquid or gas) at a transit facility. The cost of facilities and operating procedures are, for the foreseeable future, substantially higher than would be "practical" for transit operations.

Compressed methane has been used before for fleet operations, but not in the volume needed to supply a standard size bus facility. However, system development requirements for methane are small compared to hydrogen.

Life Cycle Costs

This section presents the cost that would be incurred by a transit property in owning and operating a transit bus on each of the six alternative fuels. Included in these costs are the initial costs of engine, bus and facility modifications and the recurring costs of fuel and maintenance. Research and development costs attributed to the engine conversion are not included, but are addressed in the following section on technical risks.

In view of the fact that future events are not entirely predictable, the life cycle costs presented in this section are the moderate and high petroleum price scenarios for near-, intermediate-, and long-term time periods. A low price scenario in which diesel fuels would remain the most available and most inexpensive fuel is not relevant and is not presented. Costs are thus defined for the following combinations of fuel price scenarios and time periods:

- Near-Term Scenario (1983-1985) (basis for comparison with current fuel costs)
- Moderate Price Scenario (best estimate of future prices
  - Intermediate-term (1985-1995)
  - Long-term (1995-2010)
- High Price Scenario (Petroleum supply disruptions assumed)
  - Intermediate-term (1985-1995)
  - Long-term (1995-2010).

Engine Modification Costs. The estimated cost to add a spark or glow plug ignition and convert the standard diesel to an ignition assisted diesel is $650. This price does not include any research and development costs. This option converts the diesel engine so that fuel is injected directly into the combustion chamber and ignited either by a spark plug or with the assistance of a glow plug. The original fuel injection system is retained but its capacity is increased. An ignition system is added, either a spark ignition system similar to the conventional Otto cycle engine or a glow plug installed in the combustion chamber. Electrical power must be supplied to the glow plugs during cold start and warm up.

Vehicle Modification Costs. The assisted ignition approach requires the installation of additional fuel tank capacity on the bus. This additional capacity may require more than one tank, depending on the fuel formulation. Other changes that may be required include new fuel lines, modified filler necks for the fuel tanks and the addition of auxiliary fuel pumps in the fuel supply lines.

Facility Modification Costs. Transit buses are normally fueled daily from a facility with sufficient fuel storage for several days of operation. Modifications to this fueling facility that are required for alternative fuels may include the installation of above or underground storage tanks with pumps, meters, and plumbing as well as architectural modifications required to meet safety standards. All costs are estimated for a 200-bus facility with approximately a two-day fuel storage capacity.

Fuel Costs. A diesel transit bus typically travels 34,000 miles per year and has a fuel consumption level of 3.5 miles per gallon. At this rate of fuel consumption, the bus burns approximately 37,000 Btu's of energy per mile, or 1,258 million Btu's per year. Total annual fuel costs for an alternative fuel can be estimated by multiplying its price per million Btu's by 1,258, because the assisted ignition engine is considered to burn each alternative fuel with the same efficiency as the basic diesel engine. The equation of calculating fuel cost is

Price per Million Btu's ($)	x	Number of million Btu's burned annually per bus (1,258)	=	Annual Fuel Cost per Bus ($)

Maintenance Costs. Estimates of normal and preventive maintenance costs are based on engine maintenance, vehicle maintenance, and facility maintenance.

Summary of Life Cycle Costs. The total life cycle cost is the sum of the initial costs and the recurring costs over 12 years. Both methanol and ethanol have the lowest initial cost ($1,525). The highest initial cost ($13,900) is associated with liquid hydrogen stored in a cryogenic tank.

Methane (CNG) has the lowest recurring costs (ranging from $4,200 to $5,400 less than diesel under the moderate price scenario and from $125,400 to $159,000 less than diesel under the high price scenario) because methane fuel is less expensive than diesel. Methanol recurring costs range from $69,300 to $84,900 more than diesel under the moderate price scenario and from $24,300 more to $79,500 less than the diesel under the high price scenario. Under the high price scenario all alternative fuels except ethanol appear to provide economic benefits compared to diesel fuel.

Technical Risks

The comparative economic results of the life cycle cost methodology analysis is important but is not the only factor in ranking the candidate fuels. This section discusses the technical and institutional risks and barriers to the use of an alternative fuel.

Research and Development Risks. Differentiation among alternative fuels is especially evident when the research and development costs to vehicle manufacturers are considered. There is no way of accurately estimating such costs since they are particular to individual private companies. The higher the research and development requirement, the higher the risk for small and large companies alike. Therefore, these risks can be considered barriers to the introduction of the new technology.

We assessed the development costs and risks associated with methanol and ethanol to be low; propane, ammonia and compressed natural gas to be moderate; and liquefied natural gas and hydrogen to be relatively high.

Initial Costs. The next factor that must be considered in selecting an alternative fuel for transit is the initial investment costs that each property must spend in order to use a new fuel. Once again, the fuel/engine conversion combinations with the lowest life cycle costs have a significant initial investment attached to their use. Any transit property wishing to use these fuels would be required to spend a large amount of money up front in order to potentially regain it in fuel savings in future years. This is a very difficult task for most properties since they are typically running at very high deficit levels of funding at the current time with little hope for relief in the future.

Other Risks. The analysis of technical risks has been approached from an economic standpoint such as the cost of new product developments and the initial costs to purchase new technologies. There are also institutional barriers and risks to be considered. As previously discussed, the safety procedures for the handling and transportation of each fuel is different. Some fuels, like liquid hydrogen, can be extremely dangerous if not handled properly. This type of problem requires both a technical and human behavior solution.

ALTERNATIVE FUEL SELECTION

Supply disruptions in the world-wide flow of crude oil cannot be predicted. The past decade has shown that such disruptions are not only possible but must prudently be assumed as probable unless the geopolitical structure of the petroleum market changes radically from the one that currently exists. Stand-by capability to utilize alternative fuels in diesel engines is essential since the risk of future disruptions is unknown.

Given the uncertainty of future fuel prices, transit operators should select an alternative fuel conversion approach with a low initial cost and also one that offers the flexibility of converting back to diesel for a minimal cost and reconversion time. Such an ability to utilize one fuel derived from petroleum and another from non-petroleum sources makes sense strategically. Methanol appears to be the best alternative fuel choice within this strategic context.

In ranking the six candidate fuels, we considered these key conclusions:

- The prediction of future fuel prices depends on so many political, institutional, and other non-economic and supply-related issues that the choice of any alternative to diesel fuel must be made under three different scenarios of future events. These economic projections are subject to change.

- The best alternative fuel should be one derived from natural gas, not crude oil, or one not subject to the same potential fuel disruptions as diesel fuel.

- The transit operational impacts and the economic barriers to commercialization of the engine technology are as significant as the cost implications associated with using each alternative fuel.

- The technology with the lowest requirement for research and development investment for application to diesel engines will be the first and easiest to commercialize for transit in the event of continued supply disruptions of crude oil.

- If there are no longer any supply disruptions, or the United States can reduce its petroleum imports to negate localized supply disruptions, then there is no need for an alternative fuel nor is there a clear low cost alternative to diesel fuel for transit bus use. However, this conclusion implies a level of stability in international events and the fuels market that has not been evident in the past decade.

Exhibit 4 presents a ranking of the fuels based on their suitability in the transit environment. In our judgement, methanol is the best choice for the transit industry. Ethanol could be a good alternative if its cost could be lowered by new fuel production methods, but such technology does not currently exist.

Exhibit 5 lists the alternative fuels in the order recommended for adoption by the transit industry. Recommended steps to overcome the barriers to introduction such as cost, safety, and operation considerations are discussed in this exhibit.

Fuel \ Ranking	Life Cycle Cost	Engine Technology Feasibility	Vehicle Technology Feasibility	Facility Technology Feasibility	Vehicle Operations Applicability	Facility Operations Applicability	Potential Fuel Availability	Vehicle Safety	Facility Safety	Overall Ranking
Ammonia	◒	◒	◒	◒	◒	◒	●	◒	◒	5
Ethanol	●	○	○	○	○	○	◒	○	○	2
Hydrogen	◒	●	●	●	●	●	●	●	●	6
Methane	○	●	◒	◒	●	◒	○	○	○	3
Methanol	◒	○	○	○	○	○	○	○	○	1
Propane	◒	◒	◒	◒	◒	◒	○	◒	◒	4

○ Good ◒ Fair ● Poor

Exhibit 4. Alternate Fuels Ranking

Fuel	Ranking	Barriers	Steps to Remove Barriers
Methanol	1	Engine technology	Develop low cost diesel engine
Ethanol	2	High fuel cost and engine technology	Develop low cost fuel production methods
Methane	3	Engine technology and fuel storage	Develop large Otto-cycle or new Diesel-cycle engine and fuel storage methods
Propane	4	Engine technology and fuel handling and storage	Develop engine technology and fuel handling methods
Ammonia	5	Engine technology and fuel handling and storage	Develop engine technology and fuel handling methods
Hydrogen	6	Engine technology, vehicle technology, and fuel handling and storage	Develop large Otto-cycle or new Diesel-cycle engine and completely new facilities and handling methods

Exhibit 5. Recommended Fuels

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A.C. and D.C. Advanced Propulsion Systems

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THE U.S. DOT/UMTA AC PROPULSION DEVELOPMENT PROGRAM

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The AC propulsion system development project is part of the Urban Mass Transportation Administration's (UMTA) Sub-system Technology Application to Rail Systems (STARS) program. This program has as its main objective the introduction of new technology to the US transit industry where the application of that technology may result in near-term benefits. Projects included in this program were selected from recommendations made to UMTA by an industry advisory liaison board which included representatives from all American transit authorities.

This board recommended that UMTA assign AC propulsion a high priority within the STARS program because of its high potential for reducing transit systems operating costs through:
1) Reduced maintenance because of elimination of traction motor brushes and commutators.
2) Higher power density in similar frame sizes.
3) Improved adhesion.
4) Energy savings through re-generation and higher efficiency.

The project began on March 31, 1982 when two companies, Garrett AirResearch and Westinghouse Electric Corp., were contracted to develop AC propulsion systems for installation on R-44 transit vehicles of the New York City Transit Authority (NYCTA). Early contractual tasks included analyses and plans which considered industry-wide deployment as well as specific requirements for operating on the New York system. These included reliability assurance plans, maintainability assurance plans, life cycle cost studies, energy consumption studies and test and demonstration plans.

Each contractor has selected a different solid state inverter configuration, but each has chosen pulse width modulation to provide variable voltage and variable frequency excitation for totally enclosed squirrel cage induction traction motors. Garrett has entered into an agreement with Oy Stromberg of Finland, the producer of the Helsinki Metro AC propulsion system. This agreement licenses Garrett to produce AC propulsion systems in the US using the Stromberg technology. The Westinghouse system incorporates gate turn off thyristors in a one inverter per motor configuration. This represents the first application of gate turn off thyristors in a traction system designed for the US transit industry.

To enable Government and transit industry technical evaluators to make meaningful comparisons of the two system designs, the contractors were required to construct engineering models of their system to verify their design concept and demonstrate producibility. Specification compliance tests were conducted on each model at the individual contractor's facilities. The models were also used to verify Electromagnetic Compatibility with the NYCTA signalling system and with signalling systems in general use in the transit industry. Identical test profiles which were thermally equivalent to the NYCTA RR line duty cycle were provided to each firm for use in energy studies, thermal testing and performance demonstrations. Technical performance in the specification compliance test program, content of the required plans and results of simulated operation using the RR line test profiles were used by UMTA in deciding on the continuation of the project to the vehicle test phases.

A major consideration for an AC propulsion system operation on the NYCTA is the New York policy of allowing diameters of wheels on a truck to differ by as much as 0.75 inches (1.905 cm). Load unbalances in the traction motors supplying each axle had the potential of forcing the traction motors to be severely oversized, or of requiring a compromise in the NYCTA wheel diameter maintenance policy. To evaluate the severity of this potential problem, TSC, and the AC propulsion system support contractor, N.D. Lea and Associates, completed an analysis of the proposed motor designs and the impact of altering the NYCTA wheel diameter maintenance policy. The results of that analysis are included in the following paper by Karl Berger of N.D. Lea and John Stickler of TSC.

WESTINGHOUSE/U. S. DOT AC DRIVE DEVELOPMENT USING GTO'S

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W. M. Truman
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USA

I. PROJECT OBJECTIVES

The AC Drive System developed was to meet the following objectives:

A. Demonstrate the capability to meet the acceleration and the regenerative and dynamic braking requirements of a typical Transit Property.

B. Demonstrate the capability to operate in the electromagnetic environment of a typical transit property and cause no interference with other vehicle or wayside systems.

C. Demonstrate a reduction in operating costs over other existing Propulsion Systems through increased regenerative braking capability and improved efficiencies.

D. Provide data and analysis to support the proposition of reduced motor and propulsion control maintenance costs.

The work performed by Westinghouse has been to meet these program objectives.

II. MOTORS

The motor chosen for use on the AC Drive System uses a standard 445T totally enclosed fan cooled frame. Both the rotor and stator use standard punchings. To be suitable for the transit environment, the motor uses rugged form wound coils that are wedged into the stator slots. The stator end turns are braced for support. The rotor bars are a brazed copper assembly with bars swaged in the slots. The bearings on the fan and coupling end of the motor are rated at 10,000 and 9,000 rpm, respectively, for high speed operation. The low slip motor has an efficiency of 93.3% and the 190 HP design allows a comfortable margin in the NYCTA environment while performing the function of the 120 HP R44 motors.

In addition to the totally enclosed design, a drip-proof design was also done. Although the drip-proof motor is not as impervious to the environment as the totally enclosed design, it does have a weight advantage and may be the preference of some properties. Both the totally enclosed and drip-proof motors were designed to use shaft mounted cooling fans which eliminate the need for forced cooling fans and motors. The motor weights are listed below:

Totally Enclosed	10.75" Core Length	1700 lbs
Drip-Proof	12.00" Core Length	1600 lbs
Drip-Proof	10.75" Core Length	1500 lbs
Drip-Proof	9.00" Core Length	1350 lbs

Acoustical noise measurements were made on the TEFC motor in the East Pittsburgh 1L LAB. A preliminary look at the data indicated that the noise levels were higher than the 1447 DC motor. However, it has now been shown from previous tests that the resonant effect of the 1L lab will result in noise readings higher than those obtained in an anechoic chamber by approximately 10dB. A noise test in a better environment will be used to provide final acoustical noise readings.

III. INVERTERS AND BRAKE CIRCUITS

The inverter choice for the contract is a GTO based direct fed voltage source inverter. This choice was made after making a trade study between candidate inverters. The GTO based direct fed voltage source inverter was found to be the lightest, smallest, and least expensive. The table below lists the relative costs, weights, and volumes of the candidate inverters.

INVERTER TYPE	COST	SIZE	WEIGHT
Using GTO's			
Direct fed Voltage Source	1.00	1.00	1.00
Chopper fed Voltage Source	1.31	3.13	3.44
Chopper fed Current Source	1.79	2.69	3.00
Using Thyristors			
Direct fed Voltage Source	1.49	2.69	1.94
Chopper fed Voltage Source	2.35	4.25	4.31
Chopper fed Current Source	3.18	2.81	6.19

In addition to the inverter type, the number of inverters per car was also a design consideration. The specification goal of operating two motors from a single inverter with 0.75" wheel mismatch was investigated. The wheel mismatch causes an unbalanced load sharing between the motors. In fact, under some conditions one motor could be braking while the other is in power. This causes thermal and adhesion problems in the motor that is being overloaded. Because of the wheel mismatch condition, four inverters per car were chosen rather than two. The chart below depicts the thermal problem that results when one inverter is controlling two motors.

WHEEL MISMATCH	ROTOR RESIS.	REL. MOTOR TEMP.
0.00"	LOW	1.00
0.00"	HIGH	1.30
0.75"	LOW	2.75
0.75"	HIGH	1.95

In order to obtain full electrical braking at high speeds, it is desirable to allow the motor voltage to build up rather than size the motor and inverter for high current operation. The AC motor is easily operated at higher voltage levels since it does not have a commutator to limit the voltage. In DC chopper controlled systems, the motor voltage increase that is acheived at high speed is accomplished through the use of dropping resistors.

For high speed maximum braking with the Westinghouse AC Drive Systems, a previously patented transformer circuit is used to impress voltage between the motor and the inverter. This three phase transformer circuit applies a pulse of voltage in phase with the inverter voltage wave form each half cycle to increase the effective motor voltage. The magnitude of the added voltage is a function of the transformer turns ratio and the width of the applied pulse. The primaries of the transformers are in series with the motor stator leads. The secondaries are connected to full wave diode bridges which are in turn connected to the positive DC voltage through a diode. The width of the applied voltage pulse is controlled by shorting the output of the diode bridge with a GTO. When the GTO is not conducting the voltage pulse is produced and the current generated during braking is regenerated back into the system. This is called the fully regenerative brake circuit and is the system that was built and tested in the lab. Using resistors to allow build up of motor voltage in braking is the method of the partial regeneration brake circuit. Both provide full electrical braking motor torque at high speed. The difference is in how much energy is returned to the system. The inverter itself regenerates power back to the system and with the partial regeneration circuit this would be the only regenerative energy. The partial regeneration circuit has not yet been built since for demonstration the maximum regeneration possible was desired.

Testing in the lab revealed that to obtain the full electrical brake rate listed in the specification, a higher transformer turns ratio and larger current rating GTO's may be needed. The brake rates that were measured in the lab are listed below along with the specification value.

SPEED(MPH)	48 OR LESS	50	60	70	80
SPEC VALUE	3.0	3.00	2.77	2.53	2.30
MEASURED VALUE	3.0	2.76	1.92	1.41	1.08

If the system is not fully receptive, then the dynamic brake circuit is needed to hold the regenerated voltage down to its maximum allowable value. The dynamic brake circuit consists of ten parallel resistors each of which is in series with a GTO that controls whether or not the resistor is conducting. As many resistors are turned on as are needed to bleed off the power not received by the system. One GTO is modulated on and off to provide close control of the voltage while the other GTO's are either fully on or off. The modulation of only one GTO rather than all ten together provides finer voltage control and also reduces the conducted EMI.

IV. SYSTEM WEIGHTS

The weight for one car set of AC Drive equipment is as listed below:

R44 CAM, No Regeneration, Drip-Proof Motor	13614 LBS
AC Drive, Full Regeneration, Totally Enclosed Motor	18019 LBS
AC Drive, Full Regeneration, Drip-Proof Motor	16619 LBS
AC Drive, Partial Regeneration, Totally Enclosed Motor	15319 LBS
AC Drive, Partial Regeneration, Drip-Proof Motor	13919 LBS

Comparing the R44 CAM with the AC Drive partial regeneration system one can see that the AC Drive system is only 305 lbs heavier while providing greater performance.

V. CONTROL

Each car will contain one supervisory car control package (CCP) consisting of three printed circuit boards.

The CCP reads the trainlines and sends tractive effort commands to the four motor controllers. The CCP for NYCTA will produce tractive effort commands to emulate the R44 chopper cars and thus allow training to CAM cars.

The CCP reads fault messages from the motor controllers when they individually shut down and determines if the motor controller should restart. It will try to restart unless it has already repetitively done so in which case it will leave the single motor controller with its associated inverter and motor out of service.

The CCP will detect slip or slide by comparing the four tach speed indications for the four axles. Slip or slide will be detected by checking for both excessive rate of change and differences from tach to tach. Slip detection will remove traction from the paticular axle. Slide detection will remove electrical braking from the particular axle and command removal of friction braking from the particular truck. With CAM control, traction and electrical braking can only be controlled on a whole car basis. This gives the AC drive system some traction advantage. The slip/slide control will contain a failsafe timer.

AC Drive has an inherent characteristic that would prevent slip or slide that involves rapid changes in wheel speed due to the motor slip frequency changing and changing the torque in the right direction.

For NYCTA, it has been decided that the best method for dead rail detection is to receive a safe to regenerate signal from the wayside. If this signal was not present the CCP would open the line switch and remove the vehicle electrically from the third rail.

Dynamic braking is controlled by the CCP.

For each motor, inverter, and regenerative brake circuit there will be a motor controller. One motor controller is expected to occupy one printed circuit board.

The motor controller produces the firing commands to the inverter GTO's to produce the desired variable voltage variable frequency waveforms. At low frequencies pulse width modulation (PWM) is used to produce smooth current waveforms and reduce harmonic losses. At high frequencies a straight six step wave form is used. At intermediate frequecies switching is done to place notches in the six step wave form. This is called quasi six step and is done to produce less than maximum voltage at frequencies too high for PWM. The switching notches have also been chosen in a way that minimizes harmonic losses.

The motor controller also contains the control algorithms that are used to match the torque produced by the motor with the tractive effort request from the CCP. This has been done in a noval way that determines the motor torque by measuring the input power to the inverter/brake circuit combination. In this manner, a minimum number of sensors have been used thus lowering the cost of the system and also increasing its reliability.

Both the CCP and the motor controller use Motorola 68000 16 BIT microprocessors. These devices have an exceptional computational ability that has allowed some of the new control techniques which eliminated much of the sensing hardware.

VI. PACKAGING

The packaging was done in a way that would disturb the minimum amount of equipment under the R44 vehicle. It also places the inverter in an easily accessible position. Totally enclosed boxes are used to protect the power electronics from environmental contamination and also to eliminate blower fans. This was done by making the bottom of the boxes heatsinks and using heat bricks or double-sided heatsinking. The components in the boxes were laid out so as to minimize the electrical loop distances in series with GTO's and minimize the series inductance. This relieves voltage stress and/or snubber component size.

The four modular interter packages can be located in the place of the R44 accelerating resistors. The four regeneration braking packages and four braking transformers fit in place of the R44 CAM control unit. The single dynamic brake package is placed adjacent to the regeneration braking equipment along the longitudinal center line of the vehicle. All gate driver boards for power switching devices are placed in the package containing the device.

The inverter heat sink assembly slides out for easy accessibility to components. The heat sink assembly can also be completely removed and transported on a special maintenance cart.

VII. MAINTENANCE CONCEPT

In the passenger compartment of each vehicle will be 4 lights indicating whether or not the inverters are operational. The light will indicate that all of the equipment needed to propel and brake one axle is fully operational. If, for instance, there is a failure in the regenerative brake circuit that does not affect operation in the propulsion mode the light will still be extinguished because the axle system is not totally functional. This does not mean that the equipment is not still being used in whatever way it is still functional. These lights will be latching and will be commanded from the CCP (Car Control Package).

Each day the lights should be checked and a note made of the number of failed inverters. The following action should be taken depending on the number of failed inverters:

0 Failed Inverters	Fully Operational
1 To 3 Failed Inverters	Repair At The Earliest Convenient Time
4 To 5 Failed Inverters	Remove From Service At The End Of The Day
6 To 8 FAILED INVERTERS	Remove From Service At The End Of The Run

These guidelines are based on an 8 car train and NYCTA duty.

As abnormal conditions are detected by the CCP (Car Control Package) or reported to the CCP from the MCL (Motor Control Logic) they will be retained in non-volatile memory.

When it has been determined by the CCP that the car or an inverter must be shut down this will be automatically done by the CCP and the reason for the shutdown will be stored in the non-volatile memory. As mentioned above, the inverter go light will be extinguished.

The first thing that the maintenance personnel will do to troubleshoot a failed inverter (by failed inverter is meant a failure of anything needed to drive one axle in both power and brake as indicated by the extinguished go light) is to attach a handheld terminal to the I/O port of the CCP and ask the CCP to tell in English why the equipment was taken out of service. The CCP will respond and the reason will be printed on the printer of the hand held terminal. This printout will be part of the maintenance report.

Next the maintenance personnel will initiate microprocessor self diagnostics through the hand held terminal. This will be accomplished with a simple command or a dedicated button on the terminal. The series of tests that will then be executed by the microprocessor will further define the problem; nearly to the component level. After the microprocessor has completed the self diagnostics it will list any abnormal conditions again on the terminal of the printer.

In some cases it will be necessary to use an oscilloscope or ohmmeter in conjunction with the microprocessor diagnostics to isolate the failure. This is true when a switching device is found to fail to turn on. The failure could be the logic, the gate driver, or the device. In this case the signal must be traced by looking at the input and output of the gate driver board while having the microprocessor output a continuous stream of gate commands.

With the microprocessor diagnostics, it may be possible to identify failed components on the car without taking the inverter or brake circuit to the bench for troubleshooting. Other failures may not be definable to the component level and will require bench testing.

The microprocessor diagnostics should also be used after any part or module replacement to verify that the problem is now corrected.

VIII. ELECTROMAGNETIC COMPATIBILITY

Considerable effort has been made to assure that the AC Drive System is compatible with the NYCTA track circuit signalling syystem. This work was done by Westinghouse and also by the EMI technical working group at TSC in Cambridge, MA of which Westinghouse is a participating member.

The identification and susceptibility determination of the NYCTA track circuits was done at TSC with the help of persons at NYCTA. This involved testing of track circuits at TSC and also field testing at New York conducted by TSC personnel. As a result, the 25 Hz and 60 Hz track circuits used on the NYCTA system now have identified noise susceptibility limits defined as a rail to rail voltage at the receiving end of the track circuit.

There are two modes of EMI couling. The first is termed conducted EMI. It is produced by the harmonic content of the propulsion return current flowing in the third rail and running rail(s) coupling an unwanted voltage into the track circuit receiver. This can occur any where between the train and the substation return location in both occupied and unoccupied signalling blocks. The second mode of EMI coupling is termed induced EMI. This occurs when the track circuit receiver is between the two inner axles of the vehicle. Induced EMI is a voltage produced rail to rail under the car by magnetic flux caused by switching currents in the propulsion equipment.

Conducted EMI was addressed in the following manner. To determine the rail to rail interference voltage that would result from a given 25 Hz or 60 Hz component in the DC link of each inverter of a train, a system model was developed by Westinghouse. The computer model was run for each type of track circuit identified by TSC and NYCTA. The track circuit is characterized by the susceptibility voltages, transmitter and receiver impedances, and class (single or double rail). The vehicle parameters needed are the inductance and capacitance of the input filter. With this input, the model then checks all combinations of rail permeability, number of cars in the train, and track circuit length to find the worst case conditions for both occupied and unoccupied track circuits. The computer model then outputs the worst case rail to rail voltages at the receiver end of the track circuit and the system margins found for the worst case occupied and unoccupied cases. Given early measurements of the 25 Hz and 60 Hz DC link inverter currents, the vehicle line filter inductance and capacitance needed to yield a positive margin for the worst case found for all track circuits was determined.

In the East Pittsburgh, lab, a Hall effect current transducer was placed in the DC link of the operating inverter. With an FFT spectrum analyzer data was collected of the link current spectrum at 25 Hz, 60 Hz, and in the audio frequency region. These measurements included holding the inverter at a fixed frequency and measuring worst case harmonics and also measurements of the maximum spectral values obtained while accelerating and decelerating the traction motors with maximum torque request and a simulated AW2 vehicle load. In addition to this, the output of the current transducer was amplified and applied to the input circuit of actual track circuit hardware received from NYCTA. The system modeling mentioned above defines the gain needed for the worst case system condition. Under this condition, the track circuit operated without any interference effects. The amplifier gain was then increased until interference did occur and the system margin of 2.5 for the worst cas was measured. This was done for one of the most sensitive 60 Hz track circuit. Testing in the East Pittsburgh lab was discontinued before the most sensitive 25 Hz circuit could be tested, but the EMI testing will resume again when testing begins in the new Westinghouse Transportation Division power lab. This later testing will also check whether or not the previously taken EMI data is still valid after some system redesign has been completed.

Induced EMI was expected to be quite low for the AC Drive System. Current loops were made very small to reduce the GTO series indictance. This also reduces the flux produced by the current in the loop. For chopper systems that are EMI compatible the comutating circuits of the thyristors were found to be the principle sources of induced EMI. The use of GTO's has eliminated the comutating circuits. Complete induced EMI testing will be done when testing is resumed. Test method RT/IE04A of the TSC EMI technical working group recommended testing practices will then be used.

For compatibility with NYCTA track circuits, there was an advantage in using high capacitance in the vehicle line filter. In the Westinghouse design we have taken advantage of new designs in electrolytic capacitors. These newer capacitors provide higher capacitance for the same ESR, voltage rating, and can size.

For NYCTA track circuit compatibility there is less line filter inductance needed at 60 Hz then is need at 25 Hz. For this reason, the reactor size and weight can be reduced by allowing the reactor to saturate when the inverter frequency reaches 60 Hz. The line current increases as the frequency increases (speed increases) until the base speed is reached.

IX. RELIABILITY AND LIFE CYCLE COSTS

A system simulation was done by the rail systems center at the Mellon Institute to compare the energy consumption of the R44 CAM cars with the AC Drive with full regeneration on the RR line of the NYCTA. The results showed the CAM car to consume 8.43 and 9.15 KWHPCM for empty car and fully loaded car round trip runs, respectively the results for the AC Drive system were 6.38 and 6.44 KWHPCM for empty car and fully loaded car round trip runs, respectively. This was based on a fully receptive third rail for regeneration. On the average, there was 27% energy savings calculated for the AC Drive system. The study has not yet been completed for a partially receptive third rail.

The final results for reliability and life cycle costs are being worked out by Booz-Allen & Hamilton and will be presented at the Westinghouse critical design review in the summer of 1984.

X. AREAS OF QUALITY IMPROVEMENT DISCOVERED DURING LAB TESTING OF THE WESTINGHOUSE AC DRIVE DEVELOPMENT

For the first phase of the AC Drive development, Westinghouse chose to use an existing gate driver board for the GTO's that is presently in use on industrial applications. This paticular gate driver board turned out to be a bad application for use in the traction AC Drive system. The existing board underwent several modifications to make it suitable for the application but these were not totally successful. Westinghouse is now in the process of redesigning the gate driver board to achieve an acceptible deign. The existing board appeared to have marginal turn off capability and the protection circuitry on the board was susceptible to noise.

An obvious mistake was made in the AC motor design that resulted in a lack of mechanical strength in the rotor. The deficiency resulted in failure during high speed testing. The motors will be reworked to a proper configuration for use in the remaining lab testing.

In order to achieve high effiency in the traction motor a design was chosen with a low slip motor. Full torque was achieved with 0.5 Hz slip. This design resulted in a considerable effort being spent to stabilize the control system. There is still some oscillation produced in the torque of the traction motor under closed loop control. For this reason the rotor resistance will be increased while the motors are reworked to improve their mechanical strength. This will be done by changing the material in the rotor bars and end rings. Since the present motor has a 190 HP rating in the 120 HP R44 application, increasing the slip needed for full torque can be done while still leaving ample motor thermal margin.

A somewhat out of date facility at East Pittsburgh was used for lab testing. Contained in this facility is a load simulator that was used to simulate the inertia of a vehicle by controlling the torque on DC load motors. The response of the system is fairly slow, so it is not able to simulate a pure inertia when changes in traction motor torque first appear. For future testing we will have a new facility with a new load simulator.

XI. CONCLUSIONS

Both Westinghouse and the Department of Transportation feel that the design of the AC Drive system has progressed to a point that it is applicable for use on a transit vehicle. The six month contract extension is to correct known deficiencies and produce a system that Westinghouse will be proud of for application on a vehicle for field testing.

AC TRACTION MOTOR PROPULSION SYSTEM FOR THE GARRETT/U.S. DOT AC PROPULSION PROGRAM

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Introduction

Inverter-controlled ac induction motor propulsion systems (hereafter, ac propulsion systems) are expected to be deployed by U.S. transit properties in two stages. The framework for the first stage is the Department of Transportation (DOT)-sponsored Subsystems Technology Applications to Rail Systems (STARS) Program. The objective of the STARS program is to demonstrate that a suitable ac propulsion technology already exists that meets U.S. transit requirements. The second deployment stage will be launched with an order for a preproduction series or full-production series from a transit property.

For nearly a century, transit properties throughout the world have relied exclusively on dc traction motors. Until the early 1960's, the choice was simple: dc traction motors were the only practical equipment for the propulsion system. However, for the past 15 years, since the worldwide deployment of dc chopper systems, the technology exists for introducing a practical ac traction motor drive. Indeed, in Europe ac propulsion systems are already operating in revenue service. The purpose of the STARS program is to demonstrate that such ac propulsion systems can also operate reliably in our American transit environment, are compatible with our signaling systems, and can be maintained through our maintenance practices. Successful demonstration of these technical issues and a positive result from a detailed life-cycle cost analysis will be a prerequisite to the commercialization of the ac propulsion system throughout the U.S. transit industry.

Toward that goal the Garrett approach is based on offering ac propulsion hardware developed and manufactured under license from the Finnish company, OY Stromberg, the manufacturers of the ac propulsion system for the Helsinki Metro and Rotterdam LRV, with the purpose of transferring ac propulsion technology and experience for use in the U.S. transit industry. As part of the license agreement, Garrett receives the know-how and support required to manufacture proven ac propulsion equipment in the U.S. for subsequent production programs. The benefits of this approach to the DOT and ultimately to the transit industry are minimum technical risk, lower program cost, and expeditious program completion.

This paper describes the design and development status of the ac propulsion system offered by Garrett under the STARS program. The ac propulsion system will be installed and tested in a two-car train set furnished by the New York City Transit Authority (NYCTA). The STARS program is planned in two phases. Phase I, just completed, culminated in the laboratory system testing of the full-scale prototype hardware. Phase II is expected to involve testing and evaluating two NYCTA R-44 cars at the Transportation Test Center as well as limited revenue service operation at the host property.

Ac Propulsion System

The Garrett ac propulsion equipment consists of two independent truck drives. The two drives share only those portions of the controls that are, of necessity, car-oriented (see Figure 1). Provisions are made for both automatic and manual isolation of a malfunctioning truck drive.

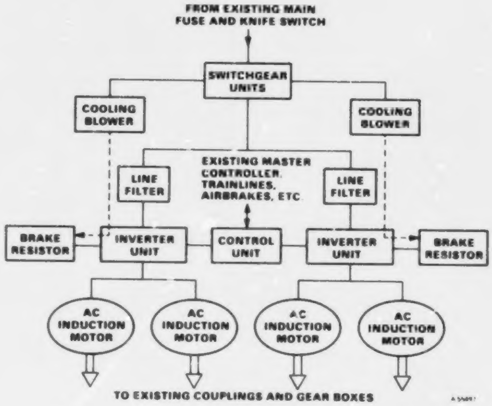

Figure 1. Ac Propulsion System (for R-44 Car)

The furnished equipment and its specifications are dictated by the intent to retrofit two NYCTA R-44 cars with ac traction motor propulsion and retain the capability of operating these cars in-train with existing cam-controlled R-44's. Trainlining and other vehicle interfaces remain unaltered. The existing master controller, P-signal generator, main fuse and knife switch, gearboxes, couplings, and the "clam shell" connectors are also retained.

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*A division of The Garrett Corporation

A single inverter unit powers two squirrel-cage induction motors in parallel. This arrangement, compared to another scheme that assigns one inverter to each traction motor, reduces the cost of equipment but does require attention to the wheel diameter differences between axles of the same truck. (This issue is addressed in detail in the section on motors.) Each inverter is cooled by a dedicated blower, the exhaust air being used to cool the brake resistor. The traction motors are totally enclosed and self-cooled.

The power circuit is shown in Figure 2. Current drawn from the third rail flows via the knife switch and main fuse to the line control equipment (LCE). The LCE contains a high-speed dc circuit breaker, a differential current relay, a contactor for blower control, contactors that switch power to the two drives (also used to isolate a faulty drive), and a contactor to switch out the inrush limiting resistor when the drive's capacitors are charged. Each drive is isolated from the line by a line filter used both for providing the required inductive source impedance to the input chopper and for EMI mitigation.

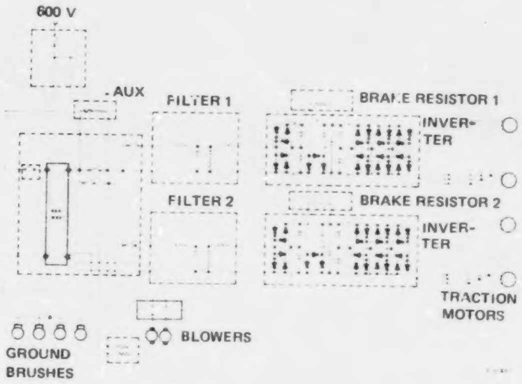

Figure 2. Electrical Power Schematic
STARS Ac Drive

The propulsion control unit (located in the cab) interfaces with the trainlines and the line control equipment by means of optical couplers for isolation from high voltage.

Normally, the controls are set to match the R-44 torque-speed characteristics and trainline command response. These characteristics are considerably less than the capability of the ac propulsion system. Consequently, an alternative (full-performance) mode is also provided that features continuous tractive effort control.

In the brake mode, a preferential blended brake control is implemented in accordance with the following order: (1) regenerative braking to the extent that the network is receptive, (2) resistive braking, wherein vehicle kinetic energy that cannot be returned to the third rail because of limited receptivity is dissipated by on-board brake resistors, and (3) friction braking, smoothly blended at very low speeds (below 5 mph).

Regeneration may be cut out by a switch located in the cab. When a truck is cut out because of a malfunction, the other truck continues to provide its rated tractive effort in motoring. However, the system reverts to friction braking because R-44 friction brake control is not implemented on a per-truck basis.

Functionally, the controls are divided into two units: (1) a car control unit, which delivers load weight compensated torque request to each of the truck control units as a function of trainline signals, and (2) two truck control units, which regulate inverter frequency and voltage so that the sum of the two traction motor torques corresponds to the commanded level.

The ac propulsion system is designed to meet the performance requirements (listed in Table 1) under specified service conditions (Table 2) and at a vehicle weight of 131,124 lb, which reflects the weight of an R-44 car with ac drive installed and at rated passenger capacity (AW2). The corresponding system capabilities are described by the maximum performance envelopes shown in Figures 3 and 4 for the drive and brake modes, respectively. When the R-44 car is emulated, these performance characteristics are appropriately reduced.

Laboratory System Test

Compliance with the specifications has been demonstrated through a laboratory system test. One complete truck drive was subjected to an extensive system test. The test was observed by DOT and transit property representatives.

A block diagram of the system test setup is shown in Figure 5. The power source was a rectifier fed by a synchronous generator. Field control was used for voltage adjustment. A resistor served as a sink for the regenerated energy. The effective value of the resistor was controlled by a chopper to match the required receptivity conditions. The ac traction motors were coupled to two industrial variable-speed drives that served as loads during motoring and drives during braking. The use of separate drives permitted simulation of wheel diameter differences. The test setup also provided for simulation of a range of transit vehicle weights.

The inverter unit (which also contains the line and brake resistor choppers), the line filter unit, the cooling air blower, and the traction motors were a production prototype configuration. The brake resistor elements and

TABLE 1

SPECIFIED PERFORMANCE REQUIREMENTS

Initial acceleration	2.5 mph/sec
Time to 70 mph	90 sec max.
Service brake rate	3.0 mph/sec below 50 mph
Linear brake taper	to 2.3 mph/sec at 80 mph
Jerk limit	2.5 mph/sec^2 (setable 1.0 to 2.5 mph/sec^2)
Maximum speed	80 mph
Maximum normal speed	70 mph (31- to 34-in. wheels)
Control	Match existing R-44 car cam controller
Duty cycle	NYCTA RR line (AW2)

TABLE 2

SPECIFIED SERVICE CONDITIONS

Line voltage	Nominal Range	600 vdc 425 to 720 vdc
Regeneration voltage limit	Setable between	600 and 720 vdc
Low voltage supply	Nominal Range	37.5 vdc 28 to 44 vdc
Wheel diameter range		31 to 34 in.
Wheel diameter difference		0.75 in. max. (between axles on same truck)
Ambient temperature		-20° to +100°F

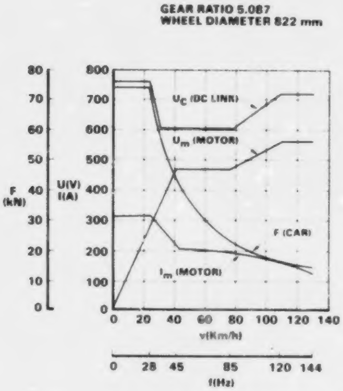

Figure 3. Drive Mode Operating Regions

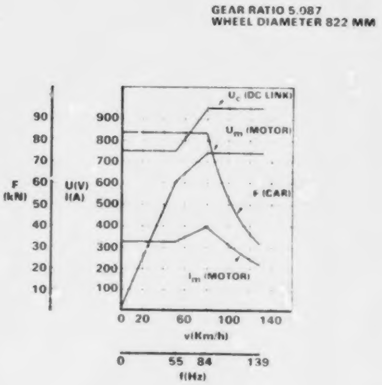

Figure 4. Brake Mode Operating Region

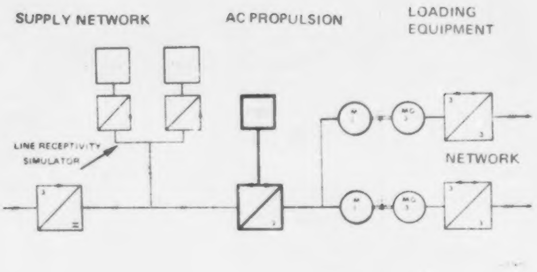

Figure 5. Ac Propulsion System Test Setup

housing were representative of production geometry and configuration to ensure valid thermal and EMI data. The electronic controls and switchgear were a prototype configuration except that they were rack-mounted for convenience. The switchgear relay logic was breadboarded.

Figure 6 shows the drive installed in the laboratory. To ensure valid inductive EMI data, the equipment was mounted in a correct geometric relationship with respect to a set of aluminum pipes used to emulate the loop formed by the running rails and vehicle axles. The traction motors were remotely located in a test cell.

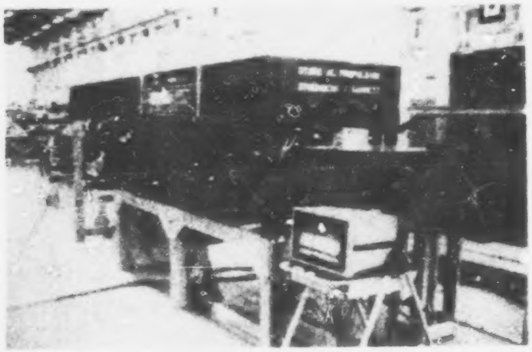

Figure 6. System Test Equipment Arrangement

The following tests and demonstrations were conducted:

Acceleration, initial rate and time to 70 mph

Maximum speed capability of 80 mph

Braking performance at zero, partial and full receptivity

Regeneration voltage limit and its setability

Capability of matching R-44 cam controller performance

Performance over rated traction supply voltage range

Performance over rated battery voltage range

Jerk limit performance and setability (1.0 to 2.5 mph/sec^2)

Response to power interruptions (power gaps)

Operation of dead-rail detector

Performance at wheel diameter differences up to 0.75 in.

Energy consumption over a synthetic route representative of the NYCTA RR-line

Thermal performance over a synthetic route (RR-line)

Response to abnormal supply and battery voltages

Thermal performance with partially blocked airflow

Abnormal stress duty cycles: long grades, successive maximum performance acceleration per brake cycles, etc.

Inductive and conductive electromagnetic emissions for signaling compatibility

The equipment met or exceeded the performance requirements during the approximately 3000-mile system test. Some principal test results are shown in Figures 7 and 8. These reflect the maximum performance mode. Time to 70 mph was 80 seconds, cutting a full 10 seconds off the 90-second requirement.

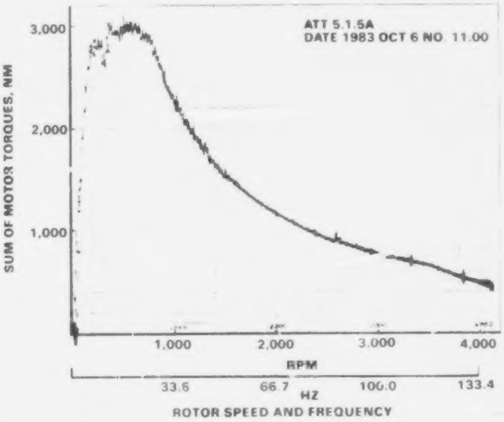

Figure 7. Performance Test Results, Acceleration

The energy consumption of the R-44 car was measured over the simulated RR-line. At an AW2 car weight, the net energy consumption is 3.2 kwhr/car-mile with regeneration, and 5.6 kwhr/car-mile in case of nonreceptive third rail. Compared to the existing cam controller-type dc propulsion system, the ac propulsion will reduce the energy consumption by 10 percent without regeneration and up to 37 percent with full regeneration.

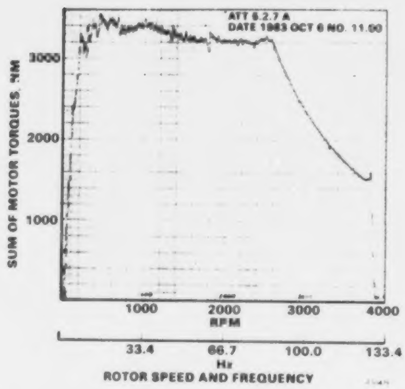

Figure 8. Performance Test Results, Braking

Prototype Hardware

Salient characteristics of the principal components of the ac propulsion system are described in this section.

Ac Traction Motors

The squirrel-cage-type ac traction motor is packaged in a totally enclosed housing, which makes it impervious to outside contaminants (see Figure 9). An integral fan forces air over external cooling fins to dissipate internally generated heat. This simple and rugged construction results in a lightweight, low-inertia motor. The electrical parts are not affected by the environment, and the motor requires minimum maintenance. The motor can interface with the existing coupling and mounting points and uses the existing gearbox. Its nameplate data are listed in Table 3.

The overall dimension of the motor is 22 in. dia by 28 in. The rotor inertia is 30.8 lb-ft^2, which is equivalent to a car mass of 3500 lb at an average speed of 15 mph over the RR route of NYCTA. As a comparison, the rotor inertia of the existing dc motor is 59.7 lb-ft^2. The lower inertia of the ac motor represents a $1500 energy saving per car over its lifetime.

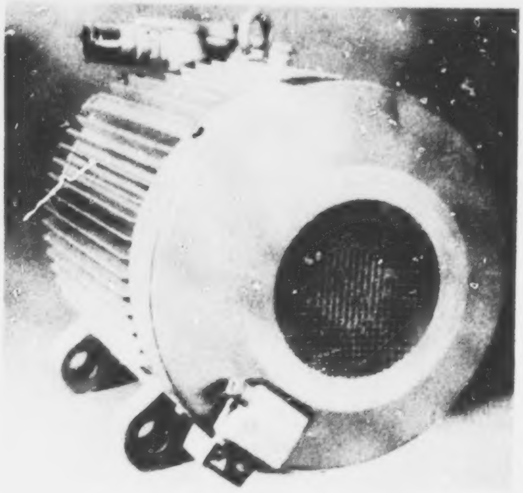

Figure 9. Totally Enclosed, Fan-Cooled (TEFC) Ac Traction Motor

In the Garrett ac propulsion system, two motors installed on a truck are supplied from a single inverter. Therefore, both motors must operate at the same frequency while a common voltage is applied to them. However, if the wheels on one of the axles of a truck have a diameter different from the wheels on the companion axle, then the two axle speeds will be different. This means that the two motors will be operating at different slips and will consequently be developing different levels of torque. The NYCTA allows up to a 3/4-in. difference between wheels on one truck.

TABLE 3

AC TRACTION MOTOR NAMEPLATE DATA

Type	HXUR/E 562G2
Power	128 kw
Voltage	470 v
Connection	D2
Current	205 amp
Frequency	45 Hz
Speed	1325 rpm
Power factor	0.83
Protection class	TEFC
Insulation class	H
Weight	606 kg

A method available for accommodating the different axle speeds is to employ traction motors designed to operate over the required range of slips with small torque change. In the case of squirrel-cage induction motors, this can be accomplished by means of selecting appropriate rotor resistance values. A relatively higher rotor resistance allows operation at a higher slip. Thus, motor designs are referred to as "high-slip," "normal-slip," and "low-slip."

The compromise that must be accepted when selecting a high-slip motor design is reduced motor efficiency and, hence, increased energy consumption. The trade-off is between net torque-per-truck capability versus overall efficiency. High-slip ac motors can provide good torque balance and, hence, a higher torque capability, but lower efficiency. Therefore, the objective is to select a motor designed for as low a slip as possible without compromising the propulsion system's acceleration performance, braking performance, or maximum speed capability.

Three ac traction motors (high-slip, normal-slip, and low-slip designs) were tested to determine their tolerance to wheel mismatch. Their normal slip was 4.4, 3.2, and 2.2 percent, respectively. The normal-slip motor design was selected because it can produce the required torque motor over the entire speed range even at a 3/4-in.-wheel-diameter difference. The net energy consumption of the ac propulsion system with a normal-slip motor is 2.87 kwhr/car-mile over the RR-line. This represents only a 4 percent higher net energy requirement compared to the low-slip motor design. At an average of 40,000 miles/year and an energy cost of $0.08/kwhr, the differential is $336/car/year, which represents a present worth of $3400. Because the normal-slip motor meets or exceeds the performance requirements, even at wheel diameter differences as high as 3/4 in., no changes are required in the NYCTA wheel maintenance practices. It is also estimated that the first cost difference between two larger versus four smaller inverters exceeds $3400. Therefore, the choice of supplying two ac traction motors from a single inverter is economically sound.

Inverter Drive Unit

The inverter drive units are solid-state motor controllers, which replace the cam controller of the dc propulsion system. The three functional subunits of the inverter drive unit are: (1) the line chopper, which controls the dc link voltage to maintain the inverter commutation capability independent of line voltage variation; (2) the inverter, which converts dc power to variable-voltage, variable-frequency ac power; and (3) the brake chopper, which controls rheostatic braking power under low-line receptivity conditions. A summary of the capabilities of the three functional subunits is listed in Table 4.

Each inverter drive unit is assembled into an open-frame structure (Figure 10), which can be rolled out as a drawer from a car body-mounted enclosure for easy maintenance. The size of the inverter unit assembled into the frame is 90 in. by 31 in. by 17 in. and weighs 1160 lb.

System Reliability

The Garrett equipment is based on the revenue service-proven ac propulsion systems for the 84 Helsinski Metro cars and 50 Rotterdam LRV's. The Helsinki and Rotterdam revenue services have shown the ac propulsion system to be extremely reliable. The reliability growth for the Helsinki system is shown in Figure 11. To date, over four million car-miles have been accumulated in revenue service. Based on the above operating experience, the predicted reliability of the Garrett propulsion system--expressed in terms of mean distance between failures (MDBF) and adjusted for corrected pattern failures and differences in equipment complexity--is 42,500 miles.

Conclusions

Garrett is offering revenue service-proven ac traction motor propulsion systems for U.S. rail transit applications. At a time when U.S. transit properties are hard-pressed to increase their efficiency and reduce their operating and maintenance costs, this timely introduction of new technology is possible because of (1) substantial ac propulsion system experience gained in Europe, (2) successful development of solid-state electrical power converters, and (3) significantly improved reliability and maintainability relative to dc propulsion systems.

Development of prototype ac propulsion systems for U.S. transit properties is being spearheaded by a DOT-sponsored program called STARS. Under the STARS program, Garrett has fabricated and successfully tested a complete truck set of ac propulsion equipment. Operational demonstration of the ac propulsion system on U.S. rail transit cars will come next.

Acknowledgments

The framework for demonstrating ac propulsion systems in the U.S. is found in the STARS program. The work reported in this paper was accomplished as part of the STARS program under contract to the Urban Mass Transportation Administration, Department of Transportation.

TABLE 4

SUMMARY OF CAPABILITIES

Inverter	
Frequency range	0.8 to 140 Hz
Continuous rated power	500 kva at 80 percent power factor
Maximum instantaneous power	950 kva
Nominal supply voltage in traction mode	600 vdc
Dc-line voltage range (inverter operational)	350 to 950 vdc
Nominal motor voltage (line to line)	470 vac
Maximum motor voltage	740 vac
Line Chopper	
Fixed operating range (crystal controlled)	425 Hz
Maximum line current (average)	605 amp
Maximum line current (momentary)	730 amp at U_C = 600 v 900 amp at U_C = 740 v
Maximum step-up chopping ratio (traction)	2
Maximum pulse width	130 µsec
Brake Chopper	
Operating frequency range	40 to 470 Hz
Maximum instantaneous power (in normal operation)	790 kw
Operating voltage range (in normal braking)	770 to 950 v
A duc/dt protection level	150 v/100 msec
Overvoltage protection level (brake chopper switches continuously on)	1050 v
Maximum duration for continuous conduction	6 sec

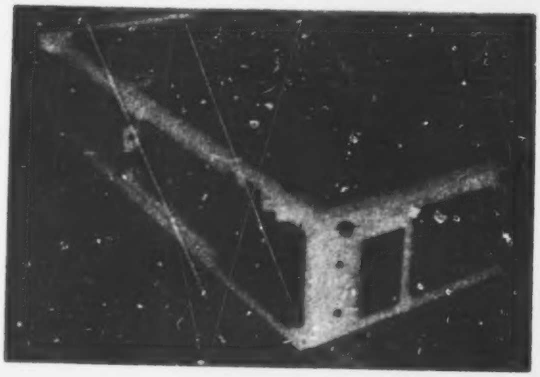

Figure 10. Inverter Drive Unit

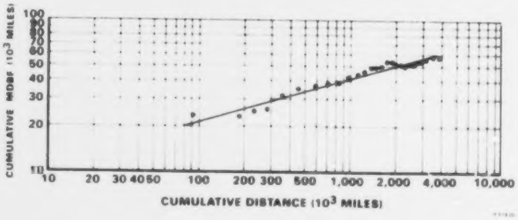

Figure 11. Ac Propulsion System Reliability Growth, Helsinki Metro Revenue Service

A. C. DRIVES FOR RAPID TRANSIT SYSTEMS — GERMAN DEVELOPMENT AND OPERATING EXPERIENCE

Wolf-Dieter Weigel
Siemens AG
West Germany

1. Introduction

Rapid transit vehicles are almost exclusively operated with d. c. line systems. Traction is conventionaly driven employing d. c. motors, controlled by means of camshaft controllers or contactors.

The predominantly intermittent mode of operation of such vehicles with frequent heavy starting and braking currents results in excessive maintenance requirements for both motors and switchgear. As a result of advances made in the field of power electronics, drives employing choppers have found increasing acceptance over the last decade. The advantages of d. c. drives with choppers are [1] :

- Continuously variable traction and braking torque leading to better utilization of the adhesion and greater passenger comfort,
- Good dynamic behaviour of the drive controls resulting in improved response to wheel slide and spin,
- Reduction of the energy requirement due to reduction of starting losses and use of regenerative braking,
- Reduction of the substation load due to reduction of starting currents in the line system and
- Reduction of maintenance requirements due to dispensing of power switchgear. The remaining switchgear for control of driving, braking and reversing is not required to switch heavy currents.

Further advantages can be gained with the use of three-phase drives:

- Reduction of the number of contacts from approximately 10 used with the chopper to between 2 and 4 for three-phase operation,
- Dispensing with the commutator and thus reduction of maintenance and unhampered installation of the motor,
- High motor speeds and thus small motors of light weight,
- Continuous field weakening without additional expense.

	Prototype car				Serial manufactured car					
City	Nuremberg	Vienna	Mülheim / Ruhr	Hamburg	Nuremberg	Berlin	Dusseldorf	Munich	Torino	Madrid
System	Light Rail	Metro	Light Rail	Metro	Metro	Metro	Light Rail	Metro	Light Rail	Metro
Number of units	1 LRV	1 DU	1 + (4) ALRV	1 AU	12 DU	6 + 39 DU	12 + 24 ALRV	6 DU	40 ALRV	[illegible] DU
Line voltage	600 V	750 V	600 V	750 V	750 V	750 V	600 / 750 V	750 V	600 V	600 V
Weight	14,9 t	55 t	28,6 t	52 t	51,2 t	38 t	41,4 t	56,7 t	35,8 t	50 t
Drive system	Longitudinal motor	Longitudinal motor	SIMOTRAC	Kardan drive	SIMOTRAC	SIMOTRAC double rotor	SIMOTRAC	Longitudinal double rotor	Longitudinal motor	Longitudinal double motor
Number of inverter	1	2	2	2	2	2	2	2	2	2
Max. driving power	250 kW	1140 kW	590 kW	720 kW	740 kW	700 kW	600 kW	875 kW	535 kW	1150 kW
Max. braking power	310 kW	2640 kW	1440 kW	2100 kW	2380 kW	1260 kW	1620 kW	2600 kW	692 kW	1520 kW
Max. d.c. link current	560 A	1130 A	560 A	800 A	1200 A	730 A	775 A	1250 A	720 A	1950 A
Max. motor speed	3000 min⁻¹	2400 min⁻¹	3600 min⁻¹	6000 min⁻¹	3600 min⁻¹	3600 min⁻¹	3600 min⁻¹	3600 min⁻¹	3660 min⁻¹	3700 min⁻¹
Max. inverter frequency	100 Hz	160 Hz	180 Hz	195 Hz	180 Hz	180 Hz	180 Hz	190 Hz	180 Hz	160 Hz
Date of delivery	1975	1978	1978	1982	1980	1980	1981	1981	1983	1984
Supplier of electrical components	Siemens	Siemens	Siemens	BBC	Siemens	AEG / Siemens	BBC / Siemens	BBC / Siemens	AEG	AEG / Siemens

Tab. 1: Rapid transit vehicles with current source inverter system

2. Three-phase drive system

As a result of extensive tests with various static converter systems in a number of prototype vehicles the current source inverter system equipped for vehicles in Nuremberg, Vienna and Muelheim/Ruhr, which have to date completed more than 400.000 km in revenue service, has gained increasing acceptance for rapid transit systems primarily due to the simple system, the simple control and the simple protection techniques.

Neither commutating thyristors, swinging circuits nor regenerative diodes are required for the selected converter configuration with interphase commutation. The commutation capacitors are normally larger than those for other self-commutating converters, since the capacitors must absorb the stray-field energy of the machine. In consequence the hold-off interval of the inverter thyristors is longer so that moderately fast types ($t_q = 120\ \mu s$), which have a higher rating than the fast types, can be employed. As a result neither series nor parallel connection of components is required in inverters within the power range employed in rapid transit systems (Table 1) up to 1200 kW.

Since the introduction of this design for series production in 1981 more than 60 vehicles each with 2 three-phase traction units have been put into revenue service in Berlin, Duesseldorf, Muelheim, Munich and Nuremberg [2, 3]. A further 100 vehicles are under manufacture. An overview on the service trial of prototypes and serial operation of a. c. drives by the german transportation authorities gives the report "Operational experience with a. c. drives in West-Germany" presented by H. J. Heider and K. Dreimann in session 2.

The design and characteristics of this type of drive will now be described. The principle of operation is depicted in Fig. 1. The chopper (CH) impresses the link current, whose magnitude is dependent on the load of the three-phase machine, to the inverter through the link reactance. The inverter distributes this current cyclically to the three windings of the machine and thus determines the frequency of the three-phase system. The currents in the machine have rectangular waveform with 120° block length. The rotor winding practically represents a short circuit to the current harmonics, so that flux in the machine is rotating nearly continuous. The terminal voltage U_M of the machine is thus sinusoidal except during commutation.

In operation, torque pulsation occurs at six times the frequency of the machine. At starting the machine current is controlled by trapezoidal pulses in order to reduce low frequency torque harmonics (Fig. 2). From Fig. 3, which

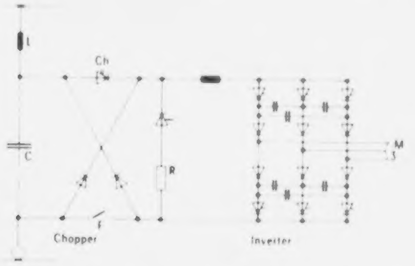

Fig. 1: Constant current link inverter

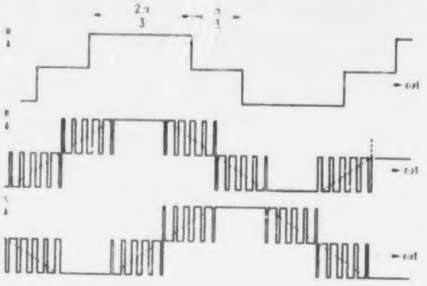

Fig. 2: Inverter pulsation

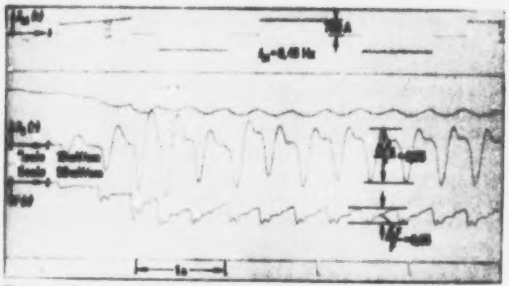

Fig. 3a: Tractive effort with rectangular wareform current

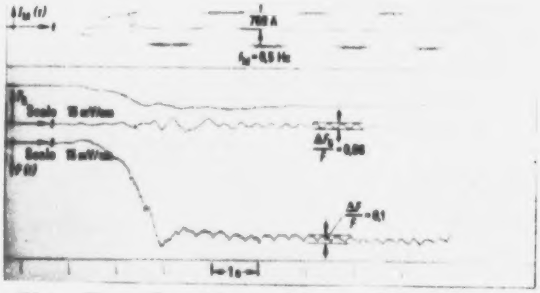

Fig. 3b: Tractive effort with PWM

is based on measurements carried out on a prototype vehicle of the subway system in Vienna, it can be seen that the harmonic of six times the frequency of the motor, which is measured at the wheels, can be reduced nearly to 10 % by using the PWM-technique [4].

Two independent drive units are generally employed to provide functional redundancy. In the case of streetcars each traction motor is fed by a converter. All axle drives are normally employed for subway vehicles so that each converter feeds two traction motors, which are connected in parallel.

3. Drive control

Field-oriented control of the drives is employed with the TRANSVEKTOR® control system, which has been widely used for speed control of three-phase motor drives [5]. As a result of this technology, for which exact speed measurement is not required and which is independent of critical machine parameters (e. g. rotor resistance), dynamic behaviour equivalent to that of d. c. fast response drives can be obtained with induction machines.

Field-oriented control is based on the fact that the operating condition (flux and torque) of an induction motor can be represented by the magnitude and direction of the stator current i_s as a space vector relative to the flux vector (Fig. 4). The current component i_μ parallel to the flux axis determines the magnitude of the flux whereas i_w is proportional to the torque. In order to determine the value of the flux-oriented steady-state variables i_μ, i_w or i_s, from the stator-oriented variables, which can only be measured at the stator terminals, and thus rotate at the supply frequency, transformation from the stator system to the flux coordinate system is necessary (Fig. 5).

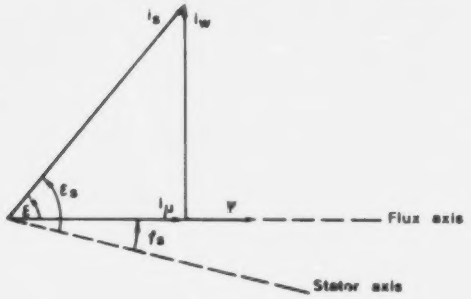

Fig. 4: Vector diagram of three-phase motor

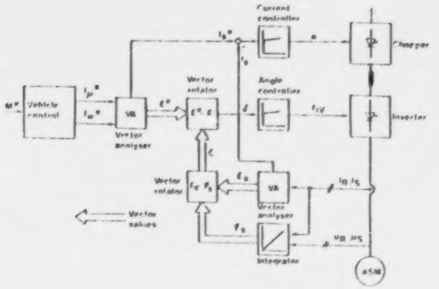

Fig. 5: TRANSVEKTOR Control System

In an initial step the continuously rotating flux vector referred to the stator axis is determined on the basis of integration of two stator voltages after compensation of the leakage reactance voltage drop. The difference between the angle ε_s, defined by the vector i_s and the stator axis, and the angle φ_s, defined by the flux vector and the stator axis, corresponds to the angle ε formed by the flux and the vector i_s, which is constant under steady-state conditions. This angle is the actual value for the phase controller, which outputs the reference value for the inverter frequency. The reference value for phase control is generated by the superordinated car control system on the basis of the desired load conditions in the form of reference values for flux and torque. The current controller compares the actual value of the stator current with the reference value and issues appropriate actuation commands to the chopper.

As a result of employment of specific modules of the TRANSVEKTOR control system vector manipulation, which at first sight appears complicated, is reduced to a task of magnitude comparable to an analog control function. Thus two "vector rotator" functions and one "vector analyser" function are implemented on a single module of dimensions 100 x 160 mm^2.

This mode of control makes possible precise definition of the operating condition and rapid torque adjustment. Thus, for example, at sliding the torque can be reduced to zero practically instantaneously, independently of the time constants of the current and flux by reducing the angle ε to zero [5].

4. Traction motors and axle drives

Nowadays twin-axle longitudinal drives are widely employed for rapid transit vehicles, in which one motor arranged longitudinally between the axles drives both axles of a bogie through bevel gearing. The objectives aimed at in this design are reduction of the number of motors and consequently reduction of the total weight of the motors and the maintenance requirements, achievement of better utilization of the adhesion as a result of solid coupling of the two axles and reduction of the tendency to slide and spin. A further stage in development is represented by the integrated twin-axle longitudinal drive (SIMOTRAC ®) in which the rotor is supported by the gearing bearings, so that no special motor bearing brackets are required [6]. This design results in reduction both of the wheelbase and of weight (Fig. 6). Most of the new three-phase cars employ this design (Table 1).

Fig. 6: Main components of a SIMOTRAC-type - Three-phase drive

The solid coupling of both axles at the classical longitudinal drive has the inconvenience of increasing wear and noise. This disadvantage can be avoided with a. c. drives by using a double rotor motor, which retains the advantages of the longitudinal drive, with a flexible coupling of the axles through the three-phase system (Fig. 7).

Two core assemblies are installed in the common stator frame of the double rotor motor and provided with a common stator winding. The wheelbase and weight can be reduced due to the dispense of two end windings. Two rotors, free to rotate with respect to each other, are mounted on the rotor supporting shaft. Torque transmission from the rotor core assembly to the gearing is effected through a flexible coupling. Since the speeds of the rotors vary only slightly as a result of slight difference in wheel diameter, simple sleeve bearings are adequate.

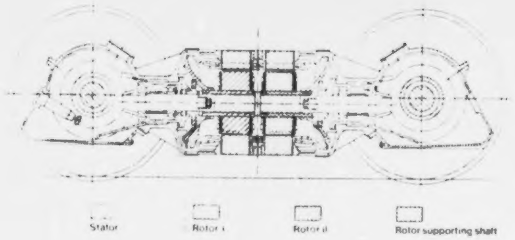

Fig. 7: SIMOTRAC drive with double rotor motor

This arrangement is electrically equivalent to series connection of two motors. The resulting torque variation due to different wheel diameters is less than that for parallel connection, since the torque characteristic for constant current is straighter over certain sections than that for constant voltage. The converter controller must control four partial machines in this case since two double rotor motors in parallel are fed by each converter. Control is effected so that the low tendency of the parallel circuit to spin is retained and that no machine is overloaded.

Up to now 48 double units for the Berlin and Munich subway systems are or will be equipped with double rotor motors.

5. Design of implemented projects

Long channel heat sink techniques have been employed for all the converters supplied. All semiconductors are mounted on heat sinks, which form a channel for the dirty cooling air (Fig. 8); dirt sensitive parts for

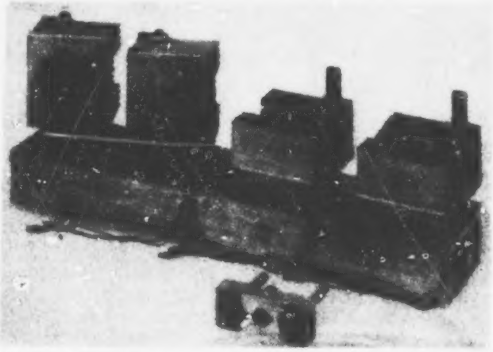

Fig. 8: Double side cooling with long channel heat sink

circuit configuration and control are installed in a separate clean chamber. According to different mechanical design of cars, operating conditions and power ratings semiconductor cooling with ribs on one side was employed in Berlin, Duesseldorf and Muelheim/Ruhr whereas double side cooling was employed in Madrid, Munich and Nuremberg.

Microcomputer controls were introduced in 1983 on these vehicles. The microcomputer control systems were custom designed to meet the specific requirements of rapid transit systems for various drive designs and permit realisation of practically all control functions by using a 8086 microprocessor. In consequence a considerable reduction of hardware is effected as compared to conventional hardwired systems. Fig. 9 depicts a conventional and a microcomputer control system for a three-phase drive system. The microcomputer controller is more reliable, allows provision of new vehicle functions, provides reproducable performance unaffected by length of service and most important of all provides numerous new monitoring functions in an integrated fault monitoring system. As a result of introduction of this new technology commissioning time is appreciably shortened primarily due to the adjustment accuracy, the full reproducibility of functions and the enhanced fault detection features [7].

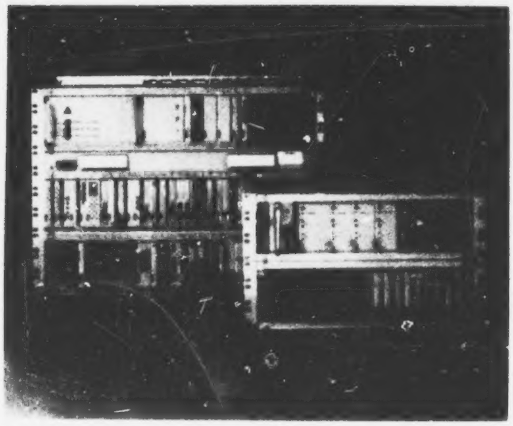

Fig. 9: Conventional and microcomputer control system for a. c. drives

6. Operating experience

Introduction of three-phase drives was on the whole unproblematic, although a number of problems did crop up. These, however, never cast doubt on the suitability of three-phase drives as such or of the drive concept. The difficulties encountered were attributable to the insufficient time available for planning and commissioning before introduction of series production on a large scale. As a result modifications had to be subsequently carried out on vehicles which had already been delivered. This experience must, however, be seen in context with the fact that major innovations in technical systems generally entail modifications based on experience gained in operation of a large number of vehicles over an extended period of service. All the vehicles supplied are in regular revenue service since they were commissioned and have since run up a total of 6 million kilometers in service. No problems have been experienced up to now with the three-phase drives and none seem likely. The reliability of the drive equipment corresponds to the value usually quoted for chopper equipment (e. g. control equipment fault rate: 1 per 100.000 km). The failure rate of the new vehicles fell below that of camshaft controlled vehicles after the first months of service [8]. Faults due to three-phase drives were rare and the majority of faults occurred in other newly developed equipment, beginning at the heating system to the axle drives.

Interference to signalling equipment and telecommunication equipment can be obviated as a result of appropriate design of the input filter, employment of low stray field techniques and suitable location of the magnetic components in addition to use of low radiation cabling. Particular care has to be taken to keep the length of leads carrying pulsating currents as short as possible, to route these appropriately and to provide adequate decoupling.

Compatibility with the signalling equipment employed in Germany was proven as a result of extensive measurements. The specified signal to noise ratio for audio frequency circuits was attained as a result of implementation of the design principles already described. In the case of track vacancy indication systems, e. g. at 50 Hz, the 50 Hz interference current occurring in normal operation is reduced to a tolerable level by suitable dimensioning of the input filter. In order to obviate the possibility of interference to the signalling system on occurrence of a fault in the drive, a fail-safe 50 Hz monitoring system is provided on these vehicles, which isolates the drive from the power system on detection of a fault. The monitor may occasionally be actuated on occurrence of sudden current changes (e. g. bouncing of pantograph), as is also the case for the signalling circuit. As a result of investigation it has been found that such transient phenomena occur also with vehicles employing camshaft controllers. The behaviour of vehicles with three-phase drives is better than that of vehicles with camshaft control due to the employment of a larger line reactance.

Electronic axle counters are not interfered with an design in accordance with the design principles described whereas in the case of point locking circuits (employing track installed coils operating at approximately 24 kHz) a reduction in the signal to noise ratio is possible as a result of insufficient selectivity under unfavourable coupling conditions (e. g. snow). In this case selectivity is increased by a modification of the signalling circuit, since in view of the sensitivity of these circuits it is not feasible to provide effective screening measures in the vehicle.

On the subways in Berlin and Nuremberg, power consumption measurements were made in revenue service over a period of several months. Two watt-meters were used to measure the energy input and output of the drives without auxiliaries. With approx. 30 % on average of energy recovery the three-phase drive technology has fully come up to expectation.

7. Further developments

Although the three-phase drive equipment described can be regarded as mature, development is continuing. On the control side microcomputers, of which mention was already made, are being introduced. 13 microcomputer controlled systems are already in service in vehicles fitted with three-phase drives. At the end of this year 24 LRT cars fitted with 48 such controls will be put into service in Duesseldorf. More than 300 controllers with microcomputer, which are employed also in camshaft controlled and d. c. chopper controlled vehicles, have been supplied or are under manufacture at present.

The chopper circuit of the power section can be simplified by the use of assymetrical or reverse conducting thyristors. Substitution of the mechanical braking contactor by a two-quadrant chopper becomes feasible. The two-quadrant chopper allows continuous control even within the range of low output voltages thus permitting electrical braking of the vehicle down to standstill.

The transition to Freon evaporation cooling will be used for the power electronic equipment. Development work is in progress in our laboratories on an emerged cooling system, which allows complete encapsulation of all components requiring cooling thus obviating the necessity to perform maintenance of the rectifier equipment. Fig. 10 depicts an prototyp inverter employing this mode of cooling. As a result of the efficient cooling of the semiconductors this system is smaller and lighter than the air cooled inverters employed in the first production models. Evaporation cooling is also employed for the smoothing reactor leading not only to a reduction in weight and volume but also to a reduction in reactance losses.

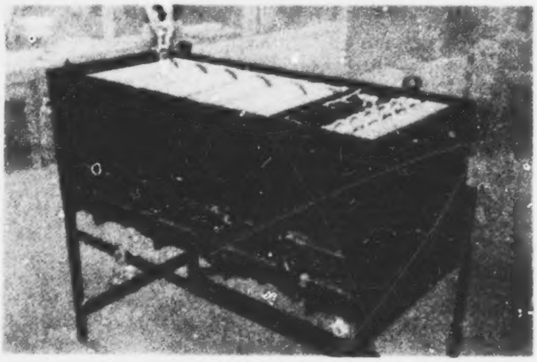
Fig. 10: Prototype inverter with Freon cooling

The developments described will be introduced in new vehicle production models. Microprocessor controls are standard for all vehicles supplied from mid 1983. The first vehicles to incorporate all the innovations described are 9 double railcars for the subway in Vienna, which was also the first to use railcars with the described three-phase drives six years ago.

Literature

[1] Scholtis, G.:
Nahverkehr und Drehstromantriebe - Aufgaben, Wünsche, Möglichkeiten.
Elektrische Bahnen 77 (1979), S. 159 - 166.

[2] N. N.:
Rheinbahn's B80D trams feature three-phase SIMOTRAC drive.
Railway Gazette International, January 1982, page 38 to 40.

[3] Fiedler, H. und Scholtis, G.:
Neue Triebwagen für die U-Bahn München. Die elektrische Ausrüstung Drehstromantriebstechnik.
Elektrische Bahnen 79 (1981), S. 381 - 387.

[4] Wagner, R.:
Der Wiener U-Bahnwagen mit Drehstromfahrmotoren.
ZEV-Glas. Ann. 103 (1979), S. 69 - 76.

[5] Bayer, K.-H.:
TRANSVEKTOR-Regelung - Ein Regelprinzip für Drehstromantriebe.
ZEV-Glas. Ann. 104 (1980), S. 291 - 298.

[6] Wagner, R.:
Drehstromantriebstechnik für Nahverkehrsbahnen.
Elektrische Bahnen 78 (1980), S. 151 - 157.

[7] Weigel, W.-D.:
Eine neue Generation von elektronischen Triebfahrzeugsteuerungen mit Mikrocomputer.
ZEV-Glas. Ann. 107 (1983), S. 305 - 312.

[8] Amler, J.:
Ein Jahr Erfahrungen mit den Nürnberger U-Bahnwagen mit Drehstromantrieb.
Verkehr und Technik 1982, H. 8, S. 295 - 302.

FREON COOLED AC MOTOR DRIVES — A COMPARISON BETWEEN CURRENT CONTROL AND PWM INVERTERS

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ABSTRACT

Most modern metros are equipped with choppers and D.C. Motors. But due to the recent progress made on power semi-conductors and with the introduction of microprocessors for logics, the cost ratio between D.C. and A.C. traction and braking equipment sets may be reversed in the near future. To this end the A.A-CEM Company built two A.C. drives for installation on existing R.A.T.P. motor coaches.

The first drive comprises a PWM inverter and has been running in revenue service without any problems since 3rd June 1982.

The second drive is a current controlled converter and will enter revenue service at the end of 1983.

The power semi-conductors are freon cooled ; this type of cooling largely out-classes the all others, and has been described in previous conferences(1)

THE SQUIRREL CAGE THREE PHASE ASYNCHRONOUS MOTOR

The asynchronous motor presents a certain number of advantages when compared to the direct current motor, for example :

- No commutator is mounted on the rotor, therefore the motor is much more robust with consequent reduction in maintenance costs.

- Improvement of power to volume and power to weight ratios permitting either, greatly increased performances for an equal volume or, an easier installation and reduced reactions on the track for an equal performance.

- Simpler manufacture thereby reducing costs :

a) Equivalent diagram and leakage inductances

Evenalthough the asynchronous motor characteristics depend on the type of supply chosen (voltage control or current control), the motor equivalent diagram per phase limited to the first harmonic is the same in both cases (fig.1a)

b) Motor leakage inductances

To reduce the voltage control inverter commutation circuits to a minimum, the motor leakage inductance must be increased to a maximum thereby reducing the motor current peaking.

On the other hand, the current control inverter commutation circuit becomes smaller as the leakage inductances become weaker because the overvoltages produced at the moment of current commutation from one phase to another are therefore reduced.

c) Motor control

Starting with a signal emanating from a master controller or an automatic pilot system and following eventual processing of the signal for transformation to a torque signal, it is necessary to generate the two variables which permit obtaining the required torque and which are :

- The current value or the motor voltage value

- The stator supply frequency value which is fed from the inverter.

VOLTAGE CONTROLLED DIRECT INVERTER

a) Control principle (fig. 2 and 3)

The inverter transforms the continuous voltage (750 V) delivered by the supply network in a system of three phase alternative voltages foreseen for the supply of the asynchronous motor.

A single cell filter Lf Cf ensures that the inverter is uncoupled with regard to the network. The filter also suppresses noise generated by the equipment and injected into the line down to an acceptable level.

Also the Cf capacity supplies the current peaks required by the inverter operation. A quick action circuit breaker DJ protects the equipment in the case of defective operation.

During the starting phase and up to the rated motor speed, the torque is held constant by imposing a maximum flux in the motor, while avoiding saturation. This is obtained by a converter progressively increasing the voltage and the frequency of the supply to the motor. If a variation in torque is desired, vary the frequency slip f2. When this supply voltage reaches a limit, we reach the region in which maximum voltage is maintained and frequency continues to increase. The flux is reduced as is the torque. In this way we obtain all the normal operating characteristics of a direct current motor, constant torque up to rated speed and constant power over and above.

b) Form of delivered signals (fig. 4)

Voltage inverters supply positive and negative voltage rectangular form pulses. These pulses are of constant amplitude but vary in width and number. By varying the widths and numbers we can artificially vary the frequency and amplitude of the wave thereby generated. For example (fig. 4) we can obtain low voltages and frequencies as seen in fig. 4.1, high frequencies and low voltages as in fig. 4.2 or high voltages and frequencies as seen in fiG. 4.3. Amplitude setting is obtained by the pulse widths and frequency by approaching or increasing the spacing between positive and negative pulses. A periodical voltage wave form is applied to the motor which results in a current of sinusoidal appearance.

The modulation employed is known as the "within cycle technique" and is particularly convenient for reducing torque pulsations while starting.

CURRENT CONTROLLED CONVERTER

a) Control principle (fig. 5)

The two functions, motor current control and frequency slip control which are in fact, torque and speed controls, are separated ; the first function being assured by a chopper while the second function is accomplished by the inverter proper.

The Lf Cf filter and the DJ circuit breaker have the same function as in the case of a voltage controlled direct inverter. During the starting phase the motor slip frequency f2 is applied : this frequency remains constant and independent of the requested torque up to motor definition speed. Torque is varied by varying the flux. Then the inverter progressively increases the supply current frequency fs, while the chopper adjusts the current to the required value which increases voltage at the motor terminals. Above the definition speed the voltage at the motor terminals cannot be increased and therefore remains constant.

The motor supply frequency continues to be increased by the inverter and to maintain constant power the slip frequency f2 is increased.

As in the case of the voltage controlled inverter the torque firstly diminishes as 1/fs.

b) Form of delivered signals (fig. 6)

The chopper supplies an adjustable assigned current of Id amplitude.

The inverter chops this current into positive and negative pulses at 120° and the voltage at the motor terminals under these conditions is practically sinusoidal.

To avoid pulsating torques at low speed starting, the pulses are themselves chopped with the aim to reducing harmonics. The motor voltage between phases has practically always the sinusoidal wave form.

SIZING OF THE TWO TRANSMISSION LINES

The voltage inverter is installed in an RATP MF 67 power car, the current inverter is installed in a MF 77 power car. In order to make a valid comparison, we extrapolated the results obtained with the MF 67 power car to an MF 77 power car. This concerns the semi-conductors, turn-off capacitors and the motor. We admit the use of semi-conductors currently existing on the market in the 1978-1980 period, that is to say during the design phase of the two projects and which essentially concerns the symetrical thyristors. We have about the same number of power semi-conductors, di/dt protective chokes and commutating capacitors for both converters.

COMPARISON BETWEEN BOTH TYPES OF CONVERTER

A comparison between both converter methods leads to the following remarks.

From the power point of view

- With regard to the motor, the type or supply makes no significant difference to the weight or size.

- The quantity of semi-conductors brought into play by each of the two filters is close, thus giving both a relative equivalent reliability.

  12 thyristors + 11 diodes for the current converter

  12 thyristors + 9 diodes for the direct inverter

The current controlled converter requires in addition to the above, one smoothing choke per motor. The advantage of weight and size tends towards the voltage inverter. This is much more apparent when no particular requirements are necessary with regard to the level of current harmonic interferences picked up by the line. This is the case of new networks where the signalling system has been adapted.

No power elements are required by the voltage controlled inverter during the passage from traction mode to braking mode. This is accomplished through the use of an electronic controlled change in frequency slip sign.

From a control point of view

It is evident that the complexity of control and the related safety problems are greater in the case of a direct inverter since the system principle leads to the use of the same subassembly for adjusting the two motor entry parameters of voltage and frequency.

We nevertheless believe that the introduction of micro-processor control will enable to attenuate the difference presently existing on this point between the two types of equipment. Nevertheless, the fact of the smoothing self's presence and that of the chopper current control, one could consider that intrinsically, the current control converter is slightly more reliable than the voltage control inverter.

If we introduce the operational qualities into the comparison, such as the pulsating torques, the network interferences and losses, we notice that both methods furnish similar results. In effect, the underchopping of the current wave at starting permits bringing down the pulsating torques harmful to the transmission to a level comparable to that obtained with the voltage direct inverter. Likewise for identical choke weightstand capacities the level of line interference will be approximately the same for the two filters.

Considering the losses and since the quantity of semi-conductors is almost the same for each filter, the global output on each typical cycle will again be very close.

CONCLUSION AND FUTURE PERSPECTIVES

In conclusion, we can say that with the direct voltage inverter, the voltages applied to the motor and semi-conductors are well under control. In the current controlled converter the currents are well under control. In the case of a severe breakdown of the control electronics, the power semi-conductors and the motors are subjected to overcurrent for a direct voltage inverter control and to overvoltage in the case of a current controlled converter.

With regard to weights, costs and reliability, the two methods are very close to one another. The choice between one or the other would be a function of the specifications to be respected (level of power required, type of line supply, line interferences tolerated on the network, type of bogie, etc.)

It will be noted that the advent of new components such as the asymetric thyristors and the G.T.Os will probably enable both devices to make appreciable savings in weight and size.

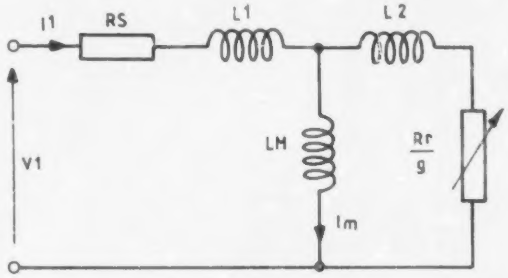
Asymetric thyristors

Assuming that the good results we have obtained up to the present are confirmed, we could then either diminish the direct voltage inverter turn-off circuit or increase the power of the motor controlled by the inverter without requiring to increase its size.

In the case of the current converter, the asymetric thyristors will permit a chopper simplification in the same fashion as above.

G.T.O.

The G.T.O. leads to the elimination of the voltage controlled inverter turn-off circuit as well as the elimination of the current converter chopper turn-off circuit.



L1 and L2 = stator and rotor leakage inductance

Lm = motor magnetising inductance

RS and Rr = stator and rotor resistance (Rs)

$g = \frac{\omega s - \omega r}{\omega s}$; ωs and ωr stator and rotor pulsations

FIGURE 1 _ EQUIVALENT DIAGRAM OF AN A.C. MOTOR

---

(1) Freon cooled choppers for trolleybus application manufactured by Alsthom- Atlantique by Jacques Soffer.
Proceedings of the first International Motor Conference - June 1981.

Choppers using boiling and condensing heat transfer for Lyons subway by E. LUCA and J.P. MOLLARD - Washington - February 1980.

Two phase freon cooling for electronic power equipment by H. ROLLET. Proceedings of the International Conference on advanced propulsion systems for Urban Rail Vehicles - Washington - February 1980.

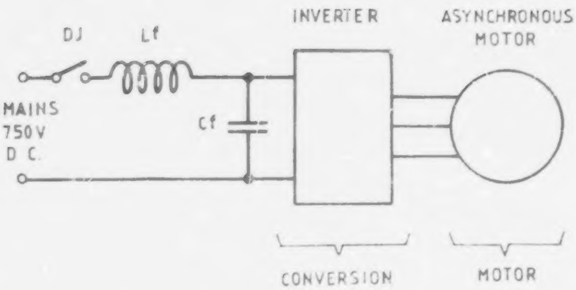

DJ
Lf
MAINS
750V
D C.
Cf
INVERTER
ASYNCHRONOUS MOTOR
CONVERSION
MOTOR

FIGURE 2 _ SUPPLY CONVERSION

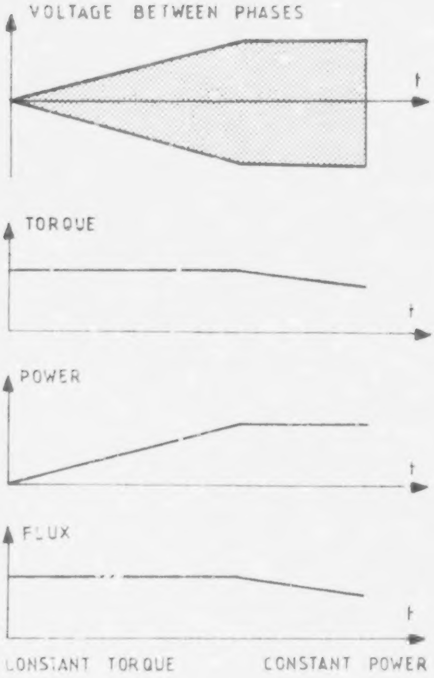


FIGURE 3 - INCREASE IN SPEED OF ASYNCHRONOUS MOTOR

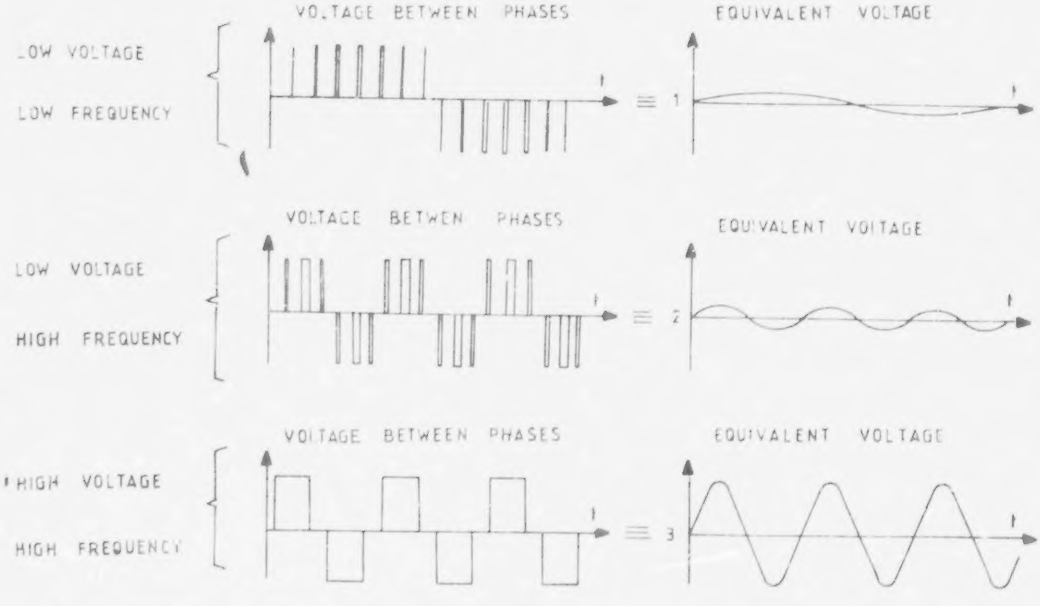

VOLTAGE BETWEEN PHASES
LOW VOLTAGE
LOW FREQUENCY
t
≡ 1
EQUIVALENT VOLTAGE
t
VOLTAGE BETWEN PHASES
LOW VOLTAGE
HIGH FREQUENCY
t
≡ 2
EQUIVALENT VOLTAGE
t
VOLTAGE BETWEEN PHASES
HIGH VOLTAGE
HIGH FREQUENCY
t
≡ 3
EQUIVALENT VOLTAGE
t

FIGURE 4 - OSO SYNCHRONOUS MODULATION

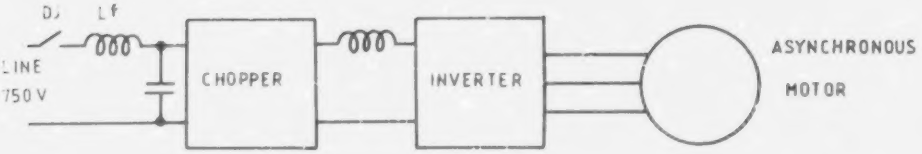

DJ
Lf
LINE
750 V
CHOPPER
INVERTER
ASYNCHRONOUS
MOTOR

FIGURE 5. CONTROL PRINCIPLE

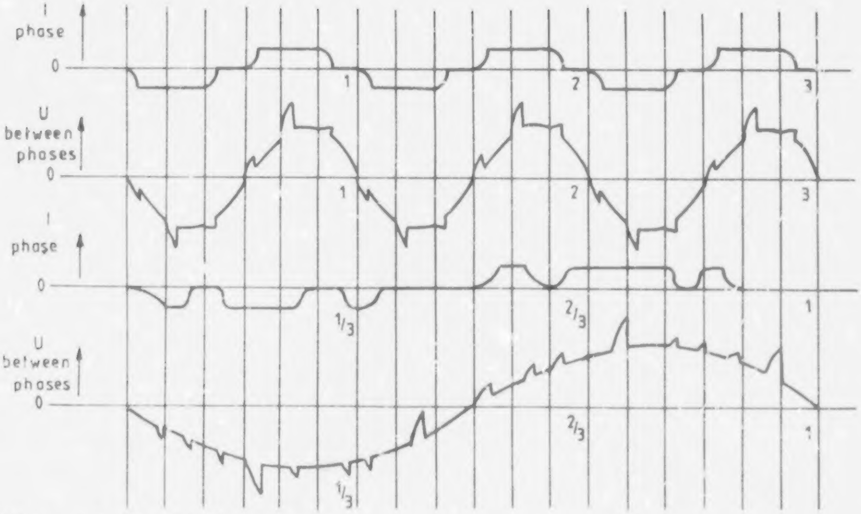


FIGURE 6 . FORM OF DELIVERED SIGNALS

ELECTRONIC POWER EQUIPMENT FOR ROLLING STOCK USING HIGH-POWER GTO

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Abstract

GTO does not require a forced commutation circuit and has many advantages compared with a thyristor. Development of GTO for high withstand voltage and current has been slow. However, semi-conductor production technology has made so rapid progress lately as to be able to supply the high-power GTO. Many kinds of the GTO's are ready for sale. The maximum power under development is that the repetitive peak off-state voltage is 4500V and the peak turn-off current is 2400A.

By applying the high-power GTO series the following electronic power equipments for rolling stock have been commercialized.

° VVVF inverter for driving induction motors
° Chopper for driving DC-series motors
° Chopper for driving DC-shunt motors
° Chopper for driving DC-compound motors
° CVCF inverter for an auxiliary power supply
° DC-DC converter for an auxiliary power supply

This paper reports the progress of development, technology, and future problems on the following three equipments among above equipments:

° VVVF inverter for driving induction motors
° Chopper for driving DC-series motors
° CVCF inverter for an auxiliary power supply

INTRODUCTION

Progress of power electronics in the electric equipment for rolling stock has rapidly been made lately accelerated by the following social needs.

They are improvement of services for passengers, reduction of power consumption, low noise, smaller sizes and lighter weights, and easy maintenance. The high-power Gate Turn Off thyristor (GTO) contributes greatly to the actualization of electronic power equipment in response to these needs. Conventional thyristors can be acclaimed a great achievement in that they initiated electronic power equipment. However, it has also the following weak points because the forced commutation circuit is required.

° Forced commutation circuitry hardware proportionally increases its size with increased equipment capacity.
° Efficiency of the equipment decreases due to the loss of the forced commutation circuit. And the treatment of the loss is difficult.
° Magnetic noise is generated from the forced commutation circuit. And direct noise is high to make it difficult to take countermeasures for inductive interference.
° Turn off time is basically long and is not capable of high-speed action.
° Commutation capacity changes depending on line voltage and can not withstand input voltage drop in lose contact or passage of section.

Above weak points are all solved by GTO without the forced commutation circuit. GTO was slow in the development for high voltage and current compared with usual thyristor. However, it is now possible to manufacture high-power GTO owing to considerable improvement in the technique of homogenous diffusion of impurities and micro-working. The line-up of high power GTO developed until now is given in Table 1.

The equipment where the high power GTO was first applied for rolling stock was the CVCF inverter. It was manufactured in 1980 and now in operation for business using GTO developed at that time whose repetitive peak off-stage voltage is 2500V and peak turn-off current is 600A.

GTO of 2500V-600A has mostly been used with 1200 applications or more mainly for CVCF inverter. Each GTO of 2500V-800A or more is used for main motor controller such as chopper or VVVF inverter.

Typical examples of power electronic equipments using high power GTO will be reported as follows.

VVVF INVERTER

The following two models so far were manufactured. One is the VVVF inverter for DC750V stringing and controlling two motors and the other is the one for DC1500V stringing and controlling four motors [1],[2]. Both are PWM modulating voltage fed inverters which have the same basic circuit system and control system with different GTO series - parallel composition because of different capacity of voltage and current. The former is composed of 1S2P of 2500V-800A GTO for one arm and the latter is composed of 2S1P of 2500V-1600A GTO for one arm. Outline of the latter equipment is described below.

Table 1 High-power GTO line-up

No	Peak repeated off voltage	Peak turn off current	Effective on current	Available years
1	4,500V	2,400A	800A	1982 trial manufacture
2	2,500V	2,000A	1000A	1983
3	2,500V	1,600A	1000A	1982 trial manufacture
4	2,500V	1,400A	700A	1982
5	2,500V	1,200A	700A	1982
6	2,500V	800A	400A	1981
7	2,500V	600A	400A	1981
8	1,300V	800A	400A	1981
9	1,300V	600A	400A	1981

Fig 1 VVVF Inverter system diagram

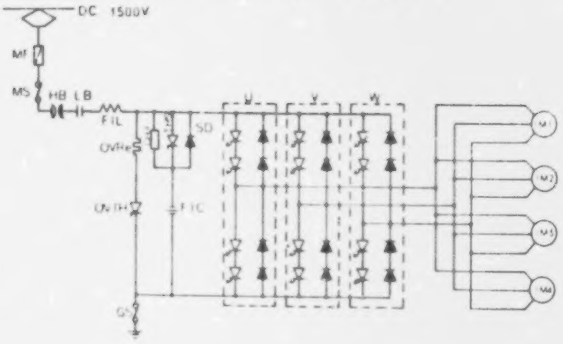
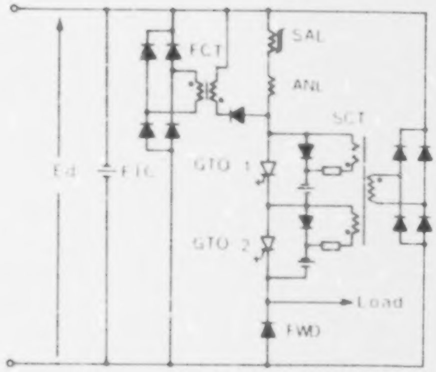


Fig. 2. Inverter arm practical implementation



Power Circuit

The main circuit connection is shown in Fig. 1. The inverter is voltage fed inverter which controls output voltage and frequency directly by the 3-phase inverter unit.

Detailed connection of each arm is shown in Fig. 2. The 2500V-1600A GTO is connected to each arm in 2S1P. SAL is a saturable reactor and controls rise of current flowing in GTO (di/dt) at turn-on time along with reactor ANL. SCT and FCT are to feedback the following two surplus energy to the input filter condenser FIC. SCT is to feedback the charged energy stored in the snubber condenser by previous turn-off at GTO turn-on time. FCT is to feedback the current energy flowing in ANL at GTO turn-off time.

The most important problem in the 2S connection of GTO is voltage balance at turn-off time. The voltage unbalance at turn-off time of 2S connection GTO is in proportion to the difference between storage times of two GTO's and the current just before turn-off and is in inverse proportion to the capacity of snubber condenser. This is formularized as follows:

$$\Delta V_s = \frac{k \cdot I \cdot |T_{s1} - T_{s2}|}{C} \qquad (1)$$

where T_{s1}, T_{s2} storage time of GTO

I Turn-off current
C Capacity of snubber condenser
k Constant

Thus it is required to make the storage time of the two GTO's equal to decrease the voltage unbalance at turn off time. It is possible to measure the storage time of GTO easily with no difficulty to make them equal.

Control

VVVF inverter has many control factors such as three control factors of output voltage, slip frequency, and modulated pulse number. Moreover, stability and quick response to frequency changes must be secured in the whole range. Accordingly, supposing that high speed and complicated function control and parameter control are required control by micro computer has been applied. High-speed processing is planned using four 8 bit micro computers and sharing control function.

The features of the control svetem are as follows. The main point is that so-called function feed forward control is used. Output voltage is given as a function of frequency keeping V/F constant except at starting time independently of output current. Proper PWM modulation ratio is operated every sampling time watching input filter condenser voltage in such a way that the output voltage defined above does not vary. Constant-current control is carried out only by slip frequency.

Test Results

Bench tests are carried out by equivalent rolling stock running tester equipped with a flywheel corresponding to four cars. The results so far obtained in the test are as follows.

1) When the difference of storage time of 2S GTO's is selected it is possible for the snubber condenser of 4μF to acquire balance of voltage share at turn-off time satisfactorily.

Fig 3 Oscillogram of DC source voltage sudden change of VVVF Inverter

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b) PWM modulation frequency was used up to 550Hz maximum and turn-off speed and loss of GTO were well enough with surplus to the designed value.

c) Heat generated by surplus energy stored in the anode reactor and snubber condenser is reduced to 1/2 or less by providing feedback CT.

d) Micro computer control has sufficient reliability with quite no malfunction and shows enough quick response and stability to the transient phenomenon like a sudden change of line voltage.
Feed forward control proves that control system has sufficient performance. The typical oscillograph of the test for line voltage sudden change is shown in Fig. 3.

For induction motor drive by VVVF inverter adhesive characteristics, inductive interference and noise are important problems besides the above. The test will be carried out successively to evaluate and confirm these themes.

CHOPPER EQUIPMENT

As choppers for driving DC series motor those of chopper frequency 250~330Hz have been manufactured using thyristors since these ten years. In using GTO for the chopper the following targets are set.

a) The smoothing reactor is removed setting chopper frequency to 990Hz using high-speed turn-off capacity of GTO.
b) Shunt chopper by GTO is set to the field system to carry out continuous weak field control.
c) Solid breakers of higher performance are applied in place of high-speed breaker for brake. (They are BS1 and BS2 in Fig. 4)

Power Circuit

Connection of main circuit is shown in Fig. 4. Armature choppers are used by 1S2P connection of 2500V-800A GTO and shunt field choppers are used by 1S1P connection of the same GTO.

In the parallel connection of GTO it is important to acquire balance of switching loss together with the balance of steady state current.
For the balance of steady state current, on-voltage of two GTO's should be equal. However, it is not enough to acquire balance of switching loss. At the turn-on of parallel connection GTO the loss occurs mostly in the GTO previously turned on, and at the turn-off the loss occurs mostly in the GTO of delayed turn-off. Generally the GTO with quick turn-on GTO is apt to be slow in curn-off and the loss of unbalance is liable to become bigger. For the switching time of GTO turn-on becomes fast as temperature rises, and turn-off becomes slow. Accordingly in the parallel connection of GTO the unbalance of loss due to the difference of switching time causes the unbalance of junction temperature and the unbalance of loss increases as the increase of difference of switching time. Thus, positive countermeasures for balance to protect the above are required. Balances reactors BL1 and BL2 are designed for the purpose.

In motoring the circuit is composed of no main smoothing reactor and in regenerating the minimum requirement of brake reactor (BSL) exists for the sake of protection and cooperation.

Fig 4 Chopper system diagram

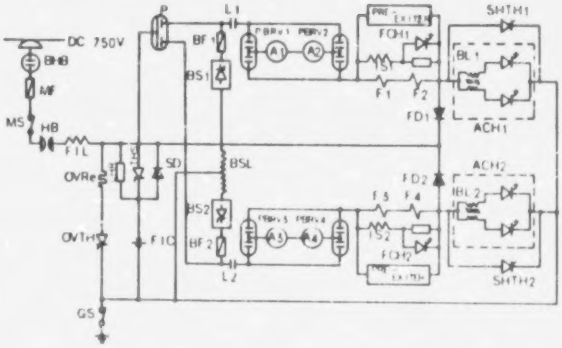
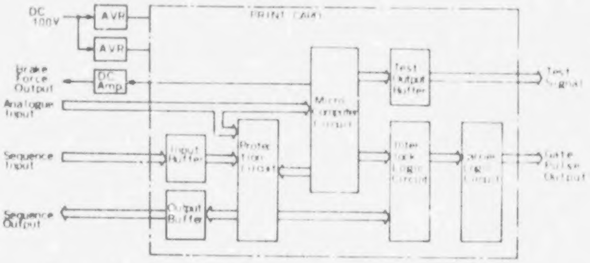


Fig 5 Hardware block diagram of Chopper control unit



Control

In the chopper equipment, as mentioned above, chopper frequency of high frequency 990Hz and continuous weak field control require response of high-speed control like VVVF inverter, and also in the chopper equipment the micro-computer control is applied.

The hardware composition of the control unit is shown in a block diagram of Fig. 5, which has roughly same scale as that of VVVF inverter.
The control system of the chopper equipment is quite different from that of VVVF inverter, however basically they carry out function feed forward control in the same way.
Counter electromotive force is operated from the detected motor revolving speed and field current and the chopper current rate is operated in such a way that a fixed armature current flows in the relation of the electromotive force and input filter cordenser voltage.
The motoring control does not have serious control problems because the armature chopper and shunt field chopper do not operate simultaneonsly. However, the two choppers operate at the same time in regenerating and the behavior of the system is so complicated that the state control algorithm is required besides function feed-forward control.

Test Results

The bench tests are carried out by the equivalent rolling stock running tester like VVVF inverter. The results obtained from the tests are shown below.

a) By using a balancer reactor of suitable capacity, it is possible to make the unbalance between current and switching loss 10% or less even in the parallel connection of GTO

Fig 6 Motoring test of Chopper

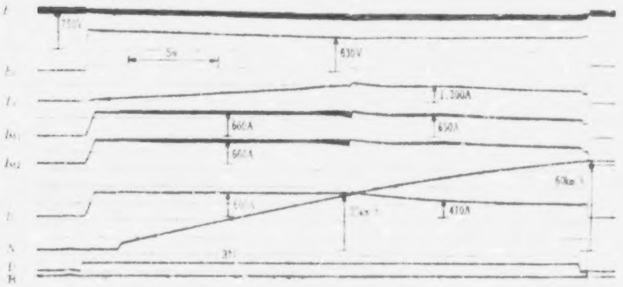
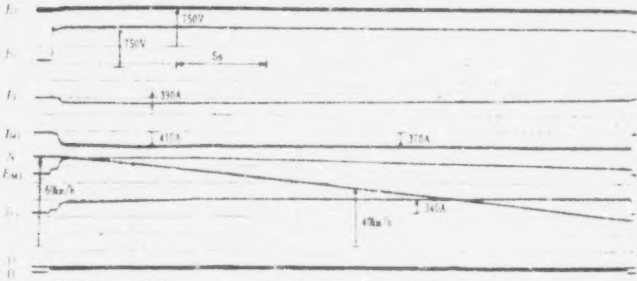


Fig 7 Regenerating test of Chopper



ES: DC Line Voltage
EC: Filter C Voltage
IS: Input Current
IM1 IM2: Armature Current
IF1: Field Current
N: Car Speed
P: Motoring Command
B: Regenerating Command
EM1: Armature Voltage

Table 2 Comparison of weight and floor area

	Resistance control equipment	Usual chopper control equipment	Developed chopper control equipment
Total weight	100%	155%	104%
Total under floor area	100%	163%	112%

b) An oscillograph of motoring test is shown in Fig. 6. Even in the motering trully without main smoothing reacter ripple current ratio is 6% or less and the commutation of the main motor is satisfactory. After short-circuit of the armature chopper, weak field control is carried out steadily by the shunt field chopper.

c) An oscillograph of regenerating is shown in Fig. 7.
In high-speed range variable field ratio control is carried out and in low-speed range full regeneration is carried out by armature chopper at the maximum field ratio and both operation is stable.

d) By using GTO and removing main smoothing reacter efficiency is improved about 4%.

e) Noise level is so reduced that it is 6 dB decrease at 1m point in front of the chopper equipment. No commutacion impulse current due to using GTO contributes much to this.

f) Accident breaking is carried out at very high speed as a usual protection by the solid breaker to give expected performance.

g) Weight and size approached nearly to as small as usual resistance control equipments. The comparison is given in Table 2 including usual thyristor chopper equipments.

CVCF INVERTER

There are many kinds of inverter of classificated by the output phase number, input voltage, and capacity. The most typical CVCF inverter of DC1500V stringing and 3-phase output is described below.

Power Circuit

Main circuit connection is shown in Fig. 8. The input filter condenser is divided into two which share a halt of each supply voltage. Both condenser voltages are supplied to the GTO inverter connected by two-set of 6-phase bridge and are converted into square wave 3-phase AC 30° out of phase by electrical angle. The phase relation of each 3-phase AC output is shown in the vector diagram of Fig. 9 and the output is multiplexed by a modified zigzag-star connection inverter transformer to eliminate the fifth and seventh higher harmonic voltage included in each AC wave form and come to 3-phase AC wave form with low distortion rate. For the control of AC output voltage to the variation of line voltage the on period of each GTO is controlled

Fig 8 CVCF Inverter system diagram

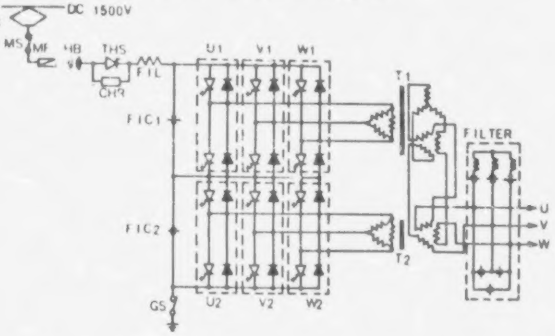


Fig 9 3-Phase AC output vector diagram of CVCF

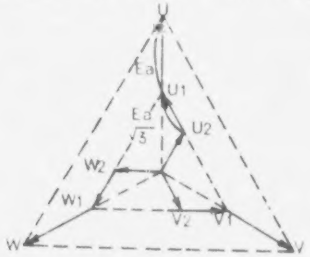


Fig 10 GTO Gate circuit block diagram of CVCF

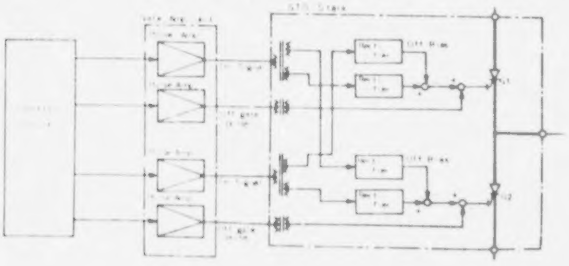


Fig 11 CVCF Inverter gate signal

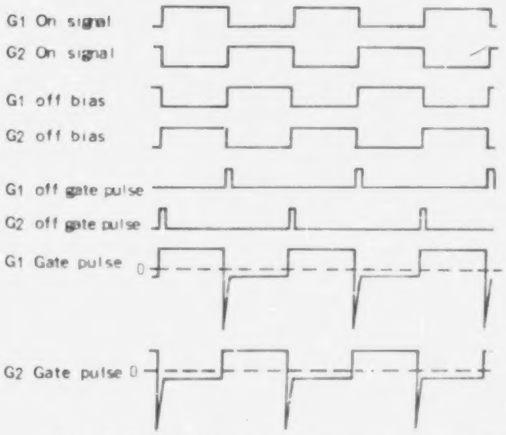


Table 3 Performance comparisons(170 KVA capacity)

	Motor-generator	GTO CVCF Inverter
Efficiency	——	15% improvement
Total Weight	100%	62%
Noise(1m)	——	15dB decrease
Maintenance	Brush inspection : every month exchange : every year Bearing greasing : every 1.5 years exchange : every 5 years	Internal cleaning : every two years

and the ratio of included fundamental wave voltage to the line voltage is changed for adjustment. The change of input voltage causes the change of included higher harmonic voltage and a filter circuit is provided so that quite low distortion rate of wave form is obtained in a full range of input voltage [3].

Gate Circuit

A gate circuit block diagram mounted with two GTO's corresponding to an inverter 1-phase is shown in Fig. 10. Each gate signal and GTO gate waveform composed in the gate circuit are shown in Fig. 11. The gate waveform of GTO is divided into three modes of the on-period, commutation period, and off-period.

On-period

In the on-state of GTO wide-width gate signal is input in the voltage fed inverter in the full period to secure on-state even at lagging power-factor.

Commutation period

In the period of GTO shift from on-state to off-state, the majority carriers of GTO base layer are discharged and a pulse circuit is used to make it possible to flow sufficient reverse current up to 1/3~1/4 of the anode current until the off-state is recovered completely.

Off-period

In the period of GTO off-state, negative bias voltage of about 3~5V is applied to the gate to improve dv/dt characteristics or to avoid misignition. In the gate circuit as shown in Fig. 12, one on-gate signal is used as the other negative bias signal using the relation that when G_1 is on G_2 is off and when G_2 is on G_1 is off.

Performance

The CVCF inverter equipment has the following three excellent advantages compared with usual rotary motor generator. That is, they are light and small-sized, low noise, and improvement of maintenance.

Great decrease of loss due to use of GTO enables closed type and complete natural cooling system to make it possible to achieve above three improvements.

Comparison of performance between the CVCF inverter and motor generator in case of 170kVA capacity is given in Table 3.

CONCLUSION

The outline of three typical electronic power equipments for rolling stock using high power GTO was described above.

It has been well proved that GTO is a powerful measure to realize light and small-sized, low noise, and high performance equipment.

However, some improvements are still required for the present high power GTO from a view point of users.

One is that turn-off gain is not so high but the volume of drive circuit for off gate pulse is far smaller than thyristor forced commutation circuit.

The another one is that the turn off time is short, however, the off gate pulse is required to continue until the decay time of the stored carrier following the turn off time.

These problems are easy to solve and future improvement of characteristics will be anticipated compared with the problems from the forced commutation circuit of reverse conducting thyristors.

The use of GTO in the electronic power equipment for rolling stock will be increased more and drive out reverse conducting thyristors soon.

REFERENCE

[1] T. Kanzaki, etal., "Direct digital controlled PWM GTO inverter for DC 1500V electric cars," IPEC TOKYO '83., vol. 2, p. 1587-1598, Mar. 1983.

[2] T. Kanzaki, etal., "Inverter control system for driving motors in rapid transit cars using high power gate turn-off thyristors," IEEE 1982 ISPCC Record, pp. 145-155, Jun 1982.

[3] T. Jinzenji, etal., "Three-phase static power supplies for air-conditioned electric coaches using high power GTO," IEEE Trans. Ind. Appli., vol IA-17, No. 2, Mar/Apr. 1981.

GTO INVERTER CONTROLLED AC TRACTION DRIVES FOR DC1500V ELECTRIC CARS

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Abstract

Hitachi carried out running tests in order to confirm reliability of GTO thyristors which are used in the circuit of VVVF inverter for DC1500V electric cars, performance of microprocessor control, and electromagnetic interference to track signal circuits.

Test showed the results that GTO thyristors endured for surge voltage and fault current and were protected perfectly, and that microprocessor fulfilled its function.

They also gave the prospect that the electromagnetic interference to the audio-frequency track circuit and the commercial frequency track circuit can be reduced to the permissible level.

Introduction

An inverter controlled AC drive system using induction motors and a variable voltage, variable fequency (VVVF) inverter has many advantages such as decreased maintenance costs of traction motors, lower power consumption, improved adhesion characteristics and so on.

In 1978, Hitachi experimetally manufactured four 130 KW induction motors and a 1500V, 1000KVA inverter, and carried out running tests in Teito Rapid Transit Authority, This inverter equipment adopted reverse conducting thyristors requiring forced commutation circuit.

Meanwhile, recently power switching devices have remarkably advanced and gate turn off (GTO) thyristors which need no commutation circuit can be practically used now.

The running tests of DC750V GTO inverter was already carried out from 1981 to 1982.[1] As the next step, Hitachi developed a 1500KVA GTO inverter-fed propulaion system for DC 1500V electric cars, and carried out running tests in 1983.

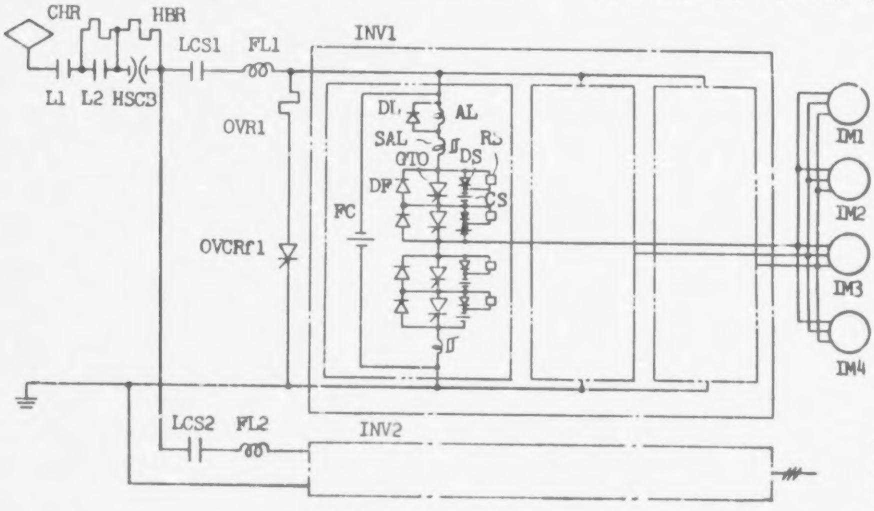
This paper describes this VVVF inverter control system and the results of running tests.

Main Circuit

Composition of Main Circuit

Generally, a VVVF inverter has three-phase circuit, and is composed of six arms (two arms a phase). Three-phase output is obtained by switching two arms of a phase alternately and controlling each arm by pulse width modulation (PWM) technique to provide 120 degrees among phases.

In Japan, a drive system of DC electric cars is usually composed of eight 150 KW class traction motors for married cars.



L1~2, LSC1~2 : Line breaker
HSCB : High-speed circuit breaker
OVCRf1~2 : Over-voltage protection thyristor
CHR : Charging resistor
HBR : Current limiting resistor
OVR1~2 : Over-voltage protection resistor
FL 1~2 : Filter reactor
INV1~2 : Inverter
FC : Filter capacitor
AL : Anode reactor
DL : Diode for anode reactor

SAL : Saturable reactor
GTO : Gate turn off thyristor
DF : Free-wheeling diode
DS : Snubber diode
RS : Snubber resistor
CS : Snubber capacitor
IM1~4 : Induction motor

Fig.1 Main circuit of VVVF inverter

Fig.1 shows the main circuit of VVVF inverter designed on this basis, but the drive system is composed of an inverter and four traction motors for a motor car in order to minimize the torgue unbalance due to the difference of wheel diameter. And, the line breaker circuit is in common for two basic drive system.

Specifications of GTO thyristor

An arm of the DC 1500V inverter main circuit has been composed of two reverse conducting thyristors of 2500V off-state voltage, 400A on-effective current class in series. The off-state voltage of GTO thyristor has to be 2500V in the case of two in series. Meanwhile, the maximum controllable current has to be considered in addition to the on-effective current about GTO thyristors. The necessary value of the maximum controllable current is calculated from the peak motor current and the performance of the over current protection system.

The number of motor cars in an electic train set can be reduced to 50%, because of the high adhesion performance of the induction motor drive system with VVVF inverter.[2] Therefore, the capacity of the traction motors increases to about 165KW, and the starting current is about 190A per traction motor. From this current, the mean current of an inverter arm is calculated by the following equation.

$$\sqrt{2}/\pi \times 190A \times 4 \doteqdot 350A$$

And the peak output current of the inverter is calculated as follows.

$$\sqrt{2} \times 190A \times 4 \times 1.2 \doteqdot 1300A$$

In this equation, "1.2" is a factor to correct the difference between the peak value of inverter output and the fundamental sinusoidal output.

Meanwhile, the maximum turn-off current of GTO thyristor is about 1800A, calculated from

1600A : setting value of over current detector in consideration of transient current at the quick change of supply voltage etc..

200A : detecting error and overshooting due to time lag of the detection and protection.

Therefore, a standard maximum controllable current of GTO thyristor is considered to be 2000A. Table 1 shows the characteristics and ratings of 2500V 2000A GTO thyristor which Hitachi developed for inverter and chopper.

Series Connection of GTO thyristors

As stated above, two GTO thyristors have to be connected in series for the DC1500V VVVF inverter. Each GTO thyristor must be protected against over voltage caused by switching due to the unbalance of turn-on or turn-off characteristics.

Table 1. Characteristics and Ratings of GTO thyristor

Item	Rating
Off-state voltage	2,500V
Maximum controllable current	2,000A
RMS on-state current	800A
Surge on-state current	14,000A
On-state voltage	1.8V (mean)
Turn-on time	6 μs
Turn-off time	30 μs
Junction temperature	− 40 to 125°C

(1) Protection method at turn-on

A saturable reactor (SAL) is connected with GTO thyristors in series in each arm in order to protect GTO thristor. The SAL will not be saturated under the supply voltage till the both GTO thyristors completely turn on.

(2) Protection method at turn-off

The capacity of snubber capacitor is decided to reduce the transient voltage from the unbalance of turn-off time below the off-state voltage of GTO thyristor, in consideration of inductance of main circuit etc..

Another protection method is the symmetrical parts arrangement of gate drive circuit for balancing the rising rates of the gate currents and minimizing the difference of turn-on or turn-off time from the unbalance of the gate current wave form.

Control Method

Control Method of Induction Motor

An induction motor essentially has a synchronous speed (No) dependent on power supply frequency (f) and number of pole (P).

$$No = 120\ f/p\ (rpm)$$

It is, therefore, necessary to control the frequency to vary the motor speed continuously. Motor torque is proportional to the product of magnetic flux in air gap and rotor current, so it is necessary to control the slip frequency, voltage applied to the motor, and motor current to adjust the air gap flux and rotor current, namely to control torque.

Fig.2 shows torque curves at different frequencies and other characteristics related with frequency, and Fig.3 shows a block diagram of the control circuits. The control method for each mode is described below.

(1) Constant torque mode

To keep the air gap flux constant, the ratio of voltage applied to the motor (V_M) and inverter frequency (f_{INV}), viz., V_M/f_{INV}, is kept constant, and to keep the rotor current constant the slip frequency (fs) is also kept constant. In consequence, motor torque and motor current are kept

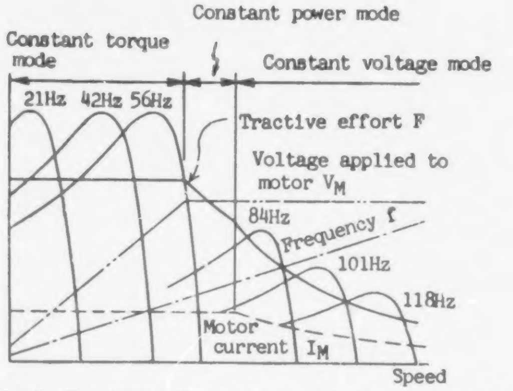


Fig.2 Tractive effort vs. speed characteristics

constant. In the actual control, motor rotating frequency (f_M) is detected by pulse generator (PG) and slip frequency is added onto it when the car is in the powering mode, and subtracted from it when the car is in the regenerative braking mode. The slip frequency is decided according to vehicle weight. V_M is controlled to keep V_M/f_{INV} constant by the V/f operation part.

(2) Constant power mode

When the voltage applied to the motor is constant, slip frequency is proportional to the inverter frequency. This corresponds to field weakening control of the DC motor. In the actual control, the motor current is kept constant by correcting the slip frequency according to the difference (I_M) of I_M detected by current detector (CT) and motor current pattern (I_{MP}).

(3) Constant voltage mode

The slip frequency (fs) is kept constant when V_M is constant at the maximum inverter output voltage. In this mode both air gap flux and rotor current decrease with increases in frequency. Therefore, motor torque is in inverse proportion to f_{INV}^2. This corresponds to the free running mode of a DC series motor.

Active damping control

The inverter system of electric cars needs an LC filter circuit at the input portion to eliminate influence from voltage ripple of a substation and to reduce interference with track signals. When this control system causes oscillation in the transient response, and when the harmonics caused by this oscillation in filter current close to the resonance frequency, the oscillation increases, making it uncontrollable. A damping circuit is adopted to suppress this oscillation. In the actual damping circuit, movement of input current is detected by a current transformer (CTS) and fs is controlled to cancel the movement of input current.

Starting control method on up-gradient track

In case of the induction motor drives controlled by the VVVF inverter, the motor requires larger current to generate adequate starting torque than usual when the electric car moves back on up-gradient track, becuase it isn't able to keep the slip frequency optimum value, and the equivalent fs becomes too high. When moving back, f_{INV} is increased by backing-speed frequency (f_M'), motor rotating frequency is minus f_M', thus equivalent fs (fs') is increased to

$$fs' = fs + f_M' - (-f_M') = fs + 2f_M'.$$

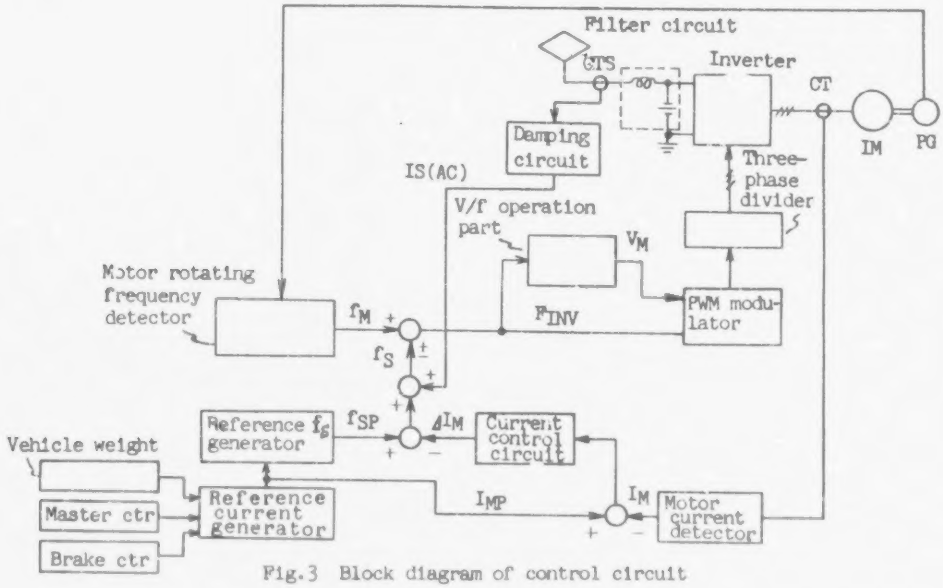

Filter circuit
CTS
Inverter
CT
IM
PG
Damping circuit
IS(AC)
Three-phase divider
V/f operation part
V_M
Motor rotating frequency detector
f_M
+
F_{INV}
PWM modulator
f_S
±
+
+
Reference f_S generator
f_{SP}
ΔI_M
Current control circuit
+
−
Vehicle weight
Reference current generator
Master ctr
Brake ctr
I_{MP}
I_M
Motor current detector
+
−

Fig.3 Block diagram of control circuit

It is necessary that either of the following two methods is realized to solve this problem without increasing controllable current of inverter.

(1) Inverter frequency control over both range of plus and minus including zero.

(2) Addition of backup system for preventing moving back on up-gradient track. For example, air brake system which operates at starting, too.

But, actually, the former is difficult with regard to frequency control around zero, and the latter is hard to be accepted to drivers because it requires change of the practice about drivers' operation or air brake system. Therefore, the following control is applied as a practical solution.

When back movement of car is detected, f_{INV} is fixed in minimum slip frequency (fs), and V_M is also kept in usual proportion to f_{INV}. According to this control, starting on up-gradient track is possible by usual drivers' operation because the motor current and torque increase within allowable level in the range of 2 ~ 3Km/h backing speed.

Outline of Inverter Equipment

Fig.4 shows an external view of the inverter equipment. The inverter equipment is composed of three units, namely three phases U,V,W, and each unit is interchangeable.

Fig.5 shows an external view of the phase unit.

The unit inverter is assembled with two Freon cooling units, filter capacitors, anode reactors, saturable reactors, gate drive units, current transformer, voltage transformer, and snubber resistors, etc..

A Freon cooling unit is assembled with the elements of one arm of inverter circuit. The cooling unit is of natural convection evaporation cooling system using Freon 113 so as to reduce maintenance cost. Heat generating parts, for example radiators or snubber resistors, are arranged to take moving air effect for efficient cooling.

Filter capacitors are assembled in the phase unit for the efficient reduction of signal interference by closing the wirings from filter capacitors to inverter circuit within the inverter equipment box, because switching current with high change rate flows through those wirings. In addition above, aluminium shielding plates are adopted to equipment enclosure (bottom and side wall). Main specificaitons of the inverter equipment are as follows.

(1) Inverter system — Voltage input inverter using pulse width modulation for output voltage control.
(2) Output capacity — 1500KVA maximum
(3) Output voltage — 0 to 1100V three phase
(4) Output frequency - 2 to 150 Hz
(5) Main thyristor — 2500V, 2000A GTO thyristor
(6) Connection of ditto - Two in series per arm
(7) Cooling system — Natural convection evaporation cooling system using Freon 113.

Fig.4 External view of the inverter equipment

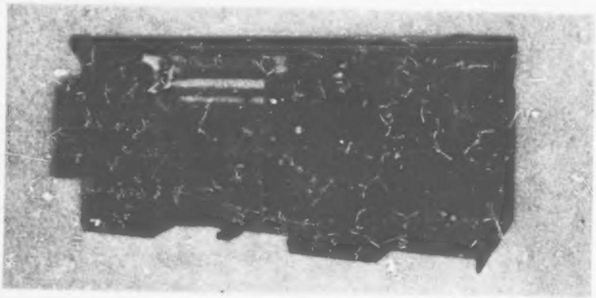


Fig.5 External view of the phase unit

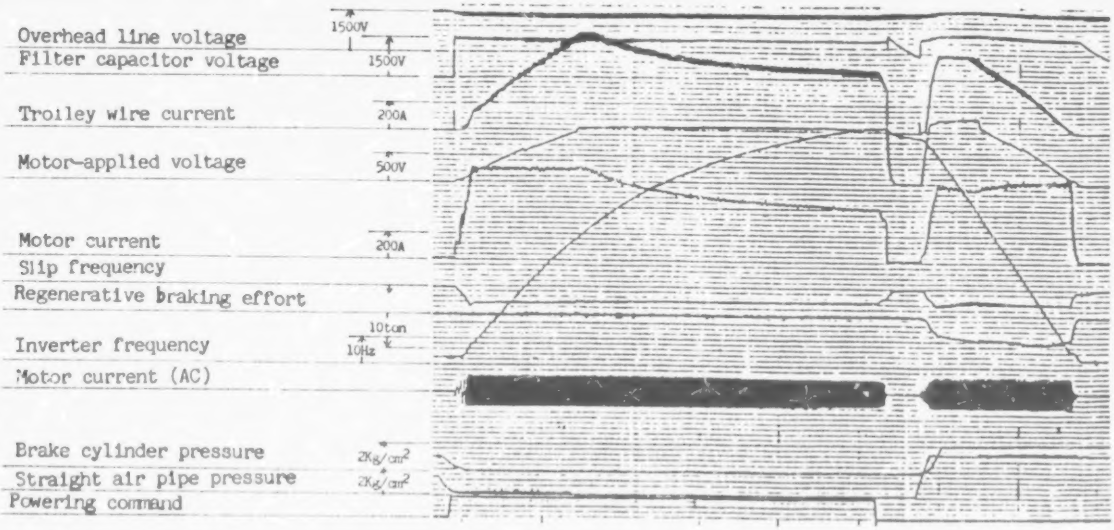


Fig.6 Oscillogram of running test.

Test Results

Acceleration and deceleration performance test

Fig.6 shows an oscillogram of the running tests. This is of powering and regenerative braking test to 80Km/h. Both powering and regenerative braking control are stable, and rising of regenerative braking current is controlled satisfactorily, too.

In addition to the acceleration and deceleration test, all of the load change test during regenerative braking, no load regenerative braking test, and power cut-off test show satisfactory results about stability and response characteristic.

Starting test on up-gradient track

Fig.7 shows an oscillogram of the starting test on 25 ‰ up-gradient track. After detecting the back movement of car, the inverter frequency is kept the slip frequency, and the motor current increases according to the backing speed. Consequently, the torque increases and the car started smoothly forward. The changeover from back movement control to usual control was smooth and no sudden torque change occurred.

Signal interference test

The most difficult technical problem in the applicaiton of VVVF inverter into existing lines must be an influence to track signal circuits. There are two kinds of signal interference, namely the influence caused by low frequency components in rail current and the influence caused by electromagnetic radiation from inverter equipment.

(1) The influence with commercial frequency track circuit by low frequency components.
Magnitude of the components is well below the minimum track relay acting current, 0.7A.

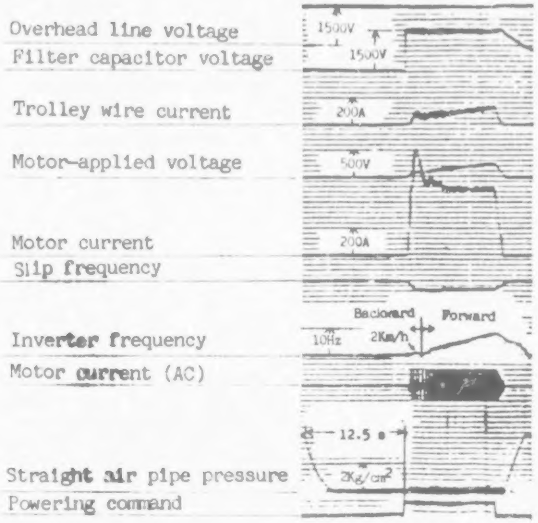


Fig.7 Oscillogram of starting test on 25‰ up-gradient track.

(2) The influence with audio-frequency track circuit by electromagnetic radiation.

Countermeasures, for example twisted wiring of main circuit, arrangement upper side of reactors, and shielding by aluminium plates, are applied to minimize the influence of electromagnetic radiation. Consequently, the interference can be reduced to the permissible level, practically.

Conclusions

As mentioned above, the problems in actual use of DC1500V GTO inverter were examined by running tests. Summeries of them are as follows.

(1) Establishment of series connection technique of GTO thyristors gave the prospect that DC 1500V GTO inverter could be used practically.

(2) Microprocessor control of VVVF inverter was confirmed that it could fulfill precise and fine control performance.

(3) Electromagnetic interference could be reduced to the permissible level, practically.

References

(1) T. Tsuboi et al.: "GTO Inverter Controlled AC Traction Drives". HITACHI REVIEW 31 (1982), No.1, P23
(2) T. Katta et al.: "Induction Motor Propulsion System for Transit Cars". HITACHI REVIEW 29 (1980). No.1, P19
(3) T. Yatsuo et al.: "Ultra High Voltage High Current Gato Turn-off Thyristors", IPEC-Tokyo '83, P65
(4) A. Ueda et al.: "GTO Inverter for AC Traction Drives", : IEEE Conference record IAS 82, Oct. 4, 1982, P645
(5) M. Ibamoto et al.: "Control System of GTO Inverter for AC Drive Transit Car". IPEC-Tokyo '83, P1509

ADVANCED CHOPPER CONTROL AND AC PROPULSION SYSTEM

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1 Abstract

We, Mitsubishi Electric, has so far promoted the development of application technology to the vehicle propulsion systems, with high power thyristors and freon cooling technique. So we have supplied a quite number of chopper control systems over the world.

Under above circumstances, new propulsion system, such as Four-Quadrant Chopper and VVVF Inverter system are entering the stage of practical application, due to the progress of power electronics and micro electronics.

Now, we have developed new Four-Quadrant Chopper, and supplied the first VVVF Inverter in Japan which has been obtaining the successful practical data.

This paper will describe both new systems, and report the results.

2 Four- Quadrant Chopper

In most conventional chopper system, several numbers of contactors are inevitably used; contactorless system is indispensable for advanced chopper system.

Owing to the greatly improved reliability of semiconductors of recent years, individually excited field control system are realized, which enables switching completely without contactors between powering and braking, forward and backward running.

As compared with conventional system, the individually excited field control system is superior in every repects. In other word, the system is provided with both advantages of armature chopper mainly applied to subway, and field chopper for suburban.

2-1 Specification

Table1 shows the main specification of the Four-Quadrant Chopper.

Table1 Specification of Four-Quadrant Chopper

Electric system	DC 600V
Train composition	3M-3T (164.7t, bare weight)
Maximum speed	70km/h
Acceleration	3.0km/h/s
Deceleration	3.5km/h/s
Traction motor	4*(120kW,300V, 440A,shh 90A)
Control system	Average current control Armature; 2-phases chopper Field ; individually excited bridge type chopper
Chopper frequency	Armature; 1kHz Field ; 250Hz

2-2 Features of Main Circuit

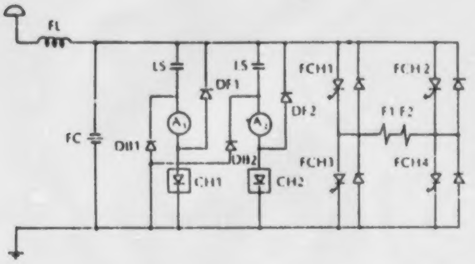
As shown in Fig.1, the armatures of the DC motors are directly connected to the high frequency choppers, and individually excited field windings are connected to the field choppers. In both choppers high power GTO thyristors are adopted.

The field chopper changes over the polarity of field current and also controls the amount of current by means of four-arm GTO thyristor switches. Thus, four operational modes can be performed;

1) forward powering
2) forward braking
3) backward powering
4) backward braking.

Hence this system is called four-quadrant chopper.

Fig.1 Circuit Diagram of Four-Quadrant Chopper



Key

A_1	No. 1 armature	DF_2	No. 2 free-wheeling diode
A_2	No. 2 armature	FCH_1	No. 1 field chopper
CH_1	No. 1 chopper	FCH_2	No. 2 field chopper
CH_2	No. 2 chopper	FCH_3	No. 3 field chopper
DB_1	No. 1 braking diode	FCH_4	No. 4 field chopper
DB_2	No. 2 braking diode	FL	Filter reactor
DF_1	No. 1 free-wheeling diode	LS	Line switch

2-3 Control System

At powering mode, FCh1 of field chopper is controlled while FCh3 is"on".

1) From starting to medium speed;

The conducting ratio of the armature chopper is increased to keep current constant, while the field current is fluctuated proportionally to the armature current. This operation is as same as that of series motor.

2) From medium to higher speed;

The speed is increased by weak field control in which the armature current kept constant by way of field control.

3) To maximum speed;

At the weakest field ratio of 40%F, the operation enters into the characteristic area of constant weak field.

At braking mode, FCh2 of field chopper is operated while FCh4 is"on". The braking effort is obtained by controlling the field current through the reverse direction, comparing to the powring mode.

At high speed area, the conducting ratio of the armature chopper is fixed almost minimum conduction ratio. In this control, the field current is controlled so that the brake torque, determined by the armature current and field current, will be equal to the brake command value.

After the field current is increased up to the maximum field ratio of 150%F, the field current is kept constant, while the armature chopper is also increased up to the maximum ratio.

2-4 Test Results

Fig.2A and Fig.2B shows the test results of Four-Quadrant Chopper.

Fig.2A Powering

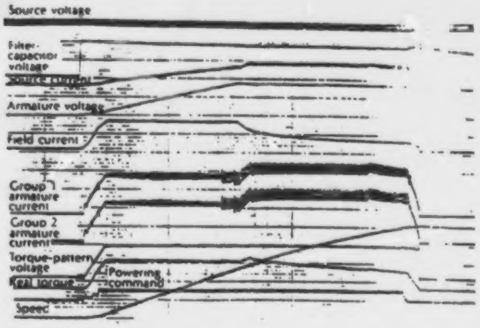
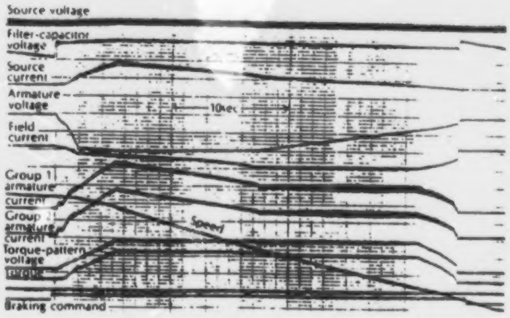


Fig.2B Braking



2-5 Appearance of Four-Quadrant Chopper

Fig.2C shows the appearance of Four-Quadrant Chopper

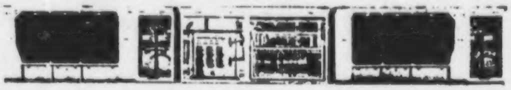


Fig.2C Appearance of Four-Quadrant Chopper

3 Advanced AC Propulsion System

We have developed the advanced propulsion with 600kW induction motor control for DC 750V line.

3-1 Specification

Table2 shows the main specification of the 1280kVA VVVF inverter.

Table2

Electric system	DC 750V (DC 500-900V)
Train composition	M-T (M: 36t, T:34t)
Maximum speed	70km/h
Acceleration	3.0km/h/s
Deceleration	3.5km/h/s
Traction motor	4*(160kW, 550V, 210A, 63Hz, 4P) Squirrel cage type
Control capacity	1280kVA/2 Inverter
Control system	3-phase, HFPWM-VVVF Inv., 1 bogie/ 1 Inv.
Control frequency	2-125Hz
Control voltage	AC 0-550V

3-2 Features of Main Circuit

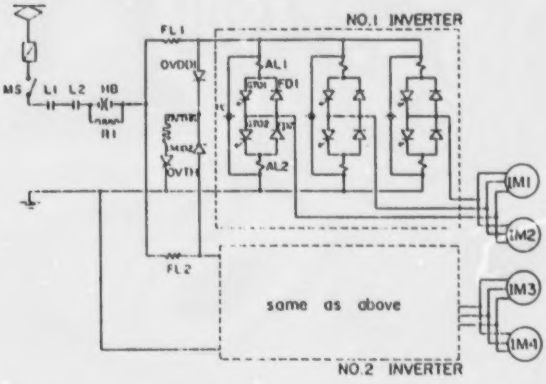


Fig.3 Circuit Diagram of VVVF Inverter

Fig.3 shows the main circuit of the VVVF Inverter system. Individual inverter units are provided for each tractive bogie. Thus, the improvements of higher adhesion, less torque mismatch between motors, and effective utilization of GTO thyristor are obtained.

Filter capacitor is mounted in one box with GTO thyristor units to suppress the electromagnetic interference, and improve the allawable anode current of GTO thyristors.

The anode reactor AL suppreses rush current, which increases when the inverter circuit is shortened.

Bogie Drive Unit(B.D.U.) control has following feature

1) High performance, such as less torque mismatch and high adhesive control,
2) Free from mismatch of wheel,
3) Fewer electromagnetic interference, due to the shorter wiring between inverter circuit and filter capacitor,
4) Redundancy for abnormal or failed case.

3-3 Control System

The performance of AC propulsion system is considered as follows;

1) Train Composition

In order to make full use of adhesion performance, the ratio of trailer car is increased.(1M-1T)

2) Adhesion

The average adhesive coefficient is designed to be approximately 18%.

3) Performance

Foundamentary, the train performance resembles DC motor system. Fig.4 shows torque curves against frequency and other characteristics.

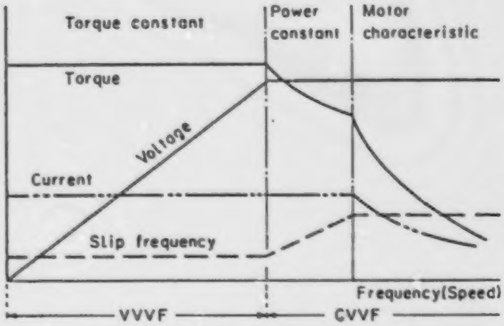
4) Powering

The constant torque, constant power and motor characteristic mode are employed.
The constant torque mode is set in a range of speed less than 1/2 of maximum speed, while the constant power mode is determined in a range of about 1/2 to 3/4 of maximum speed.

5) Regenerative braking

Similar to powering, the constant power mode is adopted.
In order to operate the braking from higher velocity, VVVF region is set 1.5 times wider than that of powering.
Also the constant power mode is provided to obtain the higher braking effort. The regenerative braking shall cover not only M-cars but also T-cars.

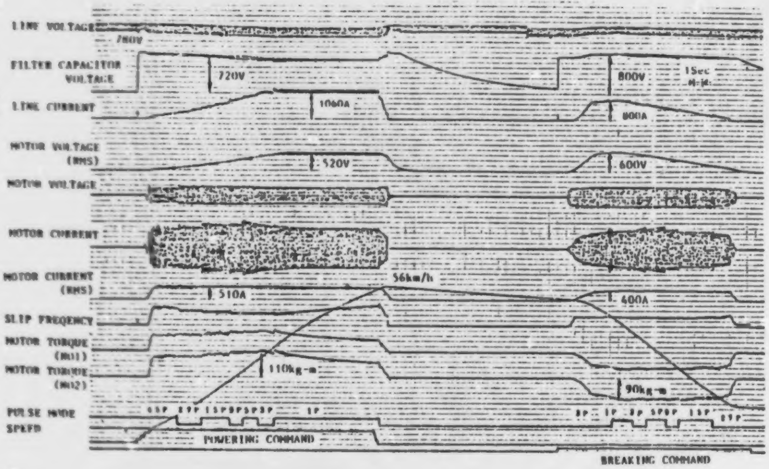
Fig.4 Tractive Effort vs. Speed Characteristics



3-4 Test Result of VVVF Inverter

Fig.5 shows the test result of powering and regenerable braking test by VVVF Inverter.

Fig.5 Test Result



3-5 Appearance of VVVF Inverter

Fig.5A shows the appearance of VVVF Inverter.

Fig.5A Appearance of VVVF Inverter

4 Device

As for the switching elements of the main circuit, both Four-Quadrant Chopper and VVVF Inverter, newly developed 1800A GTO thyristors are applied. Table3 shows the comparison of our three series of GTO thyristors. All of them are adopted in practical application.

In the main circuit, 2500V, 1800A GTO thyristors are used in 1series-1parallel connection. This brings about;

1) small size and light weight of the equipment,

2) low noise, due to the elimination of the commutation circuit

3) improved control performance by high- frequency modulation.

Table3 Ratings of GTO Thyristors

Items	FG1800A-50	FG1000A-50	FG600B-50
Repetitive peak off-state voltage	2500V	2500V	2500V
Controllable anode current	1800A	1000A	600A
RMS on-state current	860A	600A	420A
Surge on-state current	11000A	7000A	5000A
Turn-off time	20μs	15μs	15μs
Turn-off gain	5	5	5

5 Direct Digital Control System (DDC System)

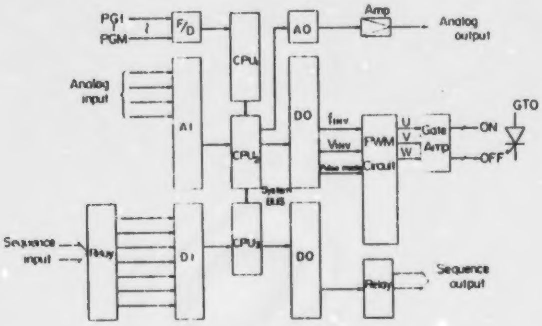
To the complicated control, such as Four-Quadrant Chopper or VVVF Inverter, stable control performance can hardly be expected only by the conventional type hardware, with discrete devices and ICs.

The control by microcomputers, which can offer free use of such as computation and judgement, is best suited. Due to the microcomputers, it is possible to take various kinds of external conditions take into account, and determine the parameters at their optimun values respectively. Moreover, the reliability become higher, and very accurate control can be expected because digital control is not affected by noise, offset and drift.

Though the protection and modulation circuits are costructed of hardware circuits, as above circuits are required high speed operation. All the other functions are carried out by the software of the microcomputers.

Fig.6 shows the hardware block diadram.(In case of VVVF Inverter)

Fig.6 Block Diagram of Control Circuit



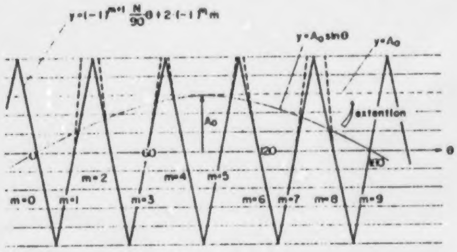
As the microcomputer unit, multi-microprocessor system is employed. Each microprocessors have respectively different functions, because of the necessity of the quick response.

They are connected thrugh the system bus-line with common memory. Taking the external conditions inside, the microcomputer gives the output of modulation rate (command signal of output voltage), frequency and number of pulses.

Arithmetic Sinusoidal Modulation system is especially applied in the VVVF Inverter, because the three-phase pulse-width modulation must be carried out. The modulation signals are obtained in the digital comparators.

To make the digital comparison easier, control of the modulation rate of sine wave is eliminated. This is realised by converting the modulation composed of the sinusoidal and triangular-waves into sine-wave modulated triangular-wave and linear line. Fig.7 shows the details of modulation wave.

Fig.7 Arithmetic Sinusoidal Modulation



6 Summary

Due to the development of high power GTO thyristor and microcomputer application technology, both high frequency Four-Quadrant Chopper and VVVF Inverter system have developed. They are scheduled to be applied to the commertial service this year.

We are now going to test these systems under 1500V adopting 4500V GTO thyristor, which has been already developed.

7 Reference

(1) A.Kaga et al.," Gate turn off thyristor application technology for rolling stock",
IEEE-IAS-1982, p.239-247.

(2) M.Ohta et al.,"TYPE-8200 AC-motor LRV for KUMAMOTO Municipul Transportation Bureau".
Mitsubishi Denki Giho , vol.56 NO.8 1982.

(3) H.Hagino et al.,"A HIGH-VOLTAGE, HIGH-POWER, FAST SWITCHING GATE TURN-OFF THYRISTOR"
IEEE-ISPEC-1982,p.66-74.

(4) T.MIyajima et al.,"Electrical characteristics of High Voltage High Power Gate Turn-off Thyristor"
IEE of Japan-IPEC-TOKYO-1983,
p. 54-61

(5) E.Akagawa et al.,"AC Propulsion System for KUMAMOTO Municipul Transportation Bureau",
IEE of Japan-IPEC-TOKYO-1983.

(6) H.Obi et al., "Advanced AC Propulsion with High Power GTO and Direct Digital Control for Electric Rolling Stock",
IEEE-IAS-1982.

THE EFFECT OF WHEEL DIAMETER DIFFERENCES ON AC INVERTER DRIVES

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1.0 INTRODUCTION

A major concern of applying ac inverter drives to U.S. transit operations is the impact of unequal wheel diameters on the maintenance of wheels and the rating of traction motors. The importance of understanding the effect of wheel diameter mismatches on system performance has prompted this study.

The objective of this study is to assess the impact of wheel diameter differences on the life cycle cost of acquiring and operating an ac inverter propulsion system for a modern rapid rail car. The study is presented in two parts. The first part describes the effect of wheel mismatch on traction motor performance, the second part describes the effect of modifying wheel trueing policy to maintain closer diameter tolerances.

2.0 BACKGROUND

Series-connected dc traction motors on bi-motor trucks do not impose any requirement for diameter matching because motor torque is a first-order function only of input current. Wheel diameter tolerance is generally held to 0.75 inches (19 mm) or less to maintain proper distribution of car weight through truck members.

The problem arising from difference in wheel diameters becomes apparent when the question of controlling two induction motors by a common inverter is considered. In such cases, unequal wheel diameters on different truck axles result in an unbalance of the traction load shared by the two motors. Since the motors must be sized to accommodate the larger of the two shared loads, the motor rating must be increased an amount dependent on the largest diameter mismatch permitted by the transit operator.

3.0 TRACTION MOTOR RATING

The approach used to study the problem arising from unequal wheel diameter on transit vehicles was to determine motor losses under a typical transit operation using an induction motor model which closely describes the performance of a real motor in operation. For this purpose, it was assumed that a host transit authority exists with defined equipment traction requirements. Based on these requirements, a representative ac induction machine was selected with nominal rating of 110 kW at 50 Hz base frequency. A computer model of the induction machine was developed to study the machine performance under typical urban rail transit conditions. Some approximations were necessarily introduced to minimize the complexity of the problem; however, the basic results are believed to be valid for the conditions considered.

3.1 Vehicle Traction Requirements

Exhibit 1 defines the traction requirements for a transit vehicle on the host property. Providing of the specified acceleration rates requires that each ac induction machine be capable of developing 3,978 lbf (17,694 N) during acceleration and 4,585 lbf (20,394 N) during braking (50 mph). The tractive effort when shared equally by each motor, i.e., equal wheel diameters, is shown in Exhibit 2 for motoring and braking modes. Above 50 mph, dynamic braking is supplemented by friction braking to reduce the motor braking power requirements.

3.2 Induction Motor Model

The motor was assumed to have four poles and power-limited at 700 rpm (110 kW). Above 1,000 rpm, the motor is operated in the field-weakening mode.

Exhibit 3 presents the induction model together with the impedance parameters used in the performance analysis. The parameters as given describe a medium/high slip type machine with rated slip of 0.06. For each operating condition given in Exhibit 1, the appropriate slip was determined consistent with the required torque demand and input line voltage.

The motor input power and ohmic losses were computed using the above equivalent circuit. Additional losses due to friction and windage, core loss, and stray loss were neglected. Motor losses P_L can be found knowing the input line current I_1 and output mechanical power p_m from,

$$P_L = 3I_1^2 R_1 + P_m \frac{S}{1-S} \qquad (1)$$

where S is the motor slip. Thus for a given motor output, the power is a function of motor slip for fixed drive voltage. For incremental slips ΔS resulting in increments in motor current ΔI_1 and torque ΔT, the power loss increment is,

$$\Delta P_L = 6I_1^2 R_1 \frac{\Delta I_1}{I_1} + \frac{P_m}{(1-S)^2} \Delta S + P_m \frac{S}{(1-S)} \frac{\Delta T}{T} \qquad (2)$$

For motor operated at slips much less than unity, Equation 2 reduces to,

$$\Delta P_L = 3I_1^2 R_1 \frac{2\Delta I_1}{I_1} + 2P_m \Delta S \qquad (3)$$

Equation 3 illustrates the linear relationship between motor loss differential and current, slip differential.

3.3 Induction Motor Loss During Transit Operation

Induction motor losses for typical urban rail transit operation were estimated based upon a given defined vehicle speed-time profile. For this purpose, a 48 mph (77 km/h) cruise speed was assumed with a total run distance of 2,700 feet (823 m). Three motor loss characteristics were generated: one for a vehicle with nominal wheel diameter - 32.375 in. (822 mm); a second for a vehicle with reduced wheel diameter - 32.0 in. (813 mm); and a third for a vehicle with enlarged wheel diameter - 33.75 in. (832 mm). The results of the motor loss calculations are presented in Exhibit 4 along with the assumed vehicle speed-time profile.

Two facts are apparent from Exhibit 4. First, the peak motor loss is increased substantially (approximately 22%) over the loss for the nominal wheel diameter case. Second, the largest motor loss during vehicle acceleration occurs for the larger wheel diameter, while the largest motor loss during vehicle deceleration occurs for the smaller wheel diameter. To a large extent, the motor loss increments over a complete acceleration/deceleration cycle cancel yielding a net motor loss which is independent of wheel diameter differential to first-order. This result could be anticipated from Equation 3 which predicts motor loss increment to be linearly proportional to motor slip increment. Since the slip increment reverses polarity over the speed profile run, the sum of the motor loss increments tends to cancel.

Motor energy consumption was found by integrating the motor power loss characteristics shown in Exhibit 4 for the different wheel diameter cases. Exhibit 5 summarizes the results for each case giving the energy during each phase of the speed-time profile as well as the total energy consumed over the profile run. From the results, one can conclude that the average motor energy loss is relatively independent of differences in vehicle wheel diameter.

3.4 Motor Rating and Cost

At present there are no domestic propulsion system manufacturers offering ac traction drives; however, two designs are being developed under the U.S. DOT STARS (Subsystem Technology Applications to Rail System) program. It will not be possible to determine the effect of motor rating on propulsion system cost with exactitude until market prices are established. However a working estimate places the cost of the nominal 110 kW motor at $15,000. The cost of increasing the peak motor rating by 22%, as required by the 0.75-inch diameter tolerance, is estimated to be approximately $1,500. The propulsion system acquisition cost would, therefore, be raised by $6,000 on a system designed to bear the 0.75-inch tolerance and proportionately less at smaller tolerances.

4.0 WHEEL SERVICING PRACTICES

The second part of this paper is concerned with the effect on maintenance cost of changing the policy limit on wheel diameter mismatch.

A study of the wheel servicing practices in several rapid rail maintenance shops indicated that the most significant source of wheel diameter reduction is caused by the wheel trueing operation as required to correct tread profile or to remove flats caused by slides during deceleration with friction brakes. Neither of these causes is significantly affected by unbalanced motor torques; therefore, ac drive does not cause additional wheel wear. Increase in the cost of wheel maintenance due to closer diameter tolerance is the result of additional labor or material required in the wheel servicing effort.

4.1 Wheel Servicing Model

The effect of diameter tolerance on wheel servicing cost was studied by simulating the maintenance operation on a digital computer. The model is presented in a simplified form as a logic flowchart in Exhibit 6. The flowchart describes the maintenance actions taken in response to the relevent conditions of the wheel sets of one truck at time of inspection which is assumed to take place every 10,000 miles (16,000 km). The extent of wear or damage between inspections is determined by an event-probability generator which uses constants derived from rail transit operating records.

Taken as pairs in a truck, there are nine possible conditions of the wheel sets at inspection. The first possibility is that neither set requires servicing. No action is taken and the simulation proceeds to the next inspection event. The second, third and fourth possibilities are that one, the other, or both wheel sets must be trued. The number of wheel sets trued (WT) is incremented as appropriate and the tolerance is checked. If the wheels are mismatched, they are brought into tolerance by cutting metal off the larger set. This reduces the service life of the wheels because more metal is removed than necessary to correct damage; however, it is less costly than exchanging wheel sets with a matching pair.

The remaining five possibilities involve scrapping one or both wheel sets of the truck due to irreparable damage or because the wheels have worn to the condemning limit. Scrapped wheel sets are replaced by sets found in a search of good used stock and the number of wheel sets removed from trucks (WP) is incremented. If no match is found then stock is searched for mating wheel sets first among used stock, or, ultimately two new sets are installed, which increments the count of wheel sets used (WU).

4.2 Model Results

The model is run for 500 inspections, which simulates 5 million car-miles. This simulation is repeated for a range of diameter tolerances so that a curve can be fitted to the results. Exhibit 7 shows the number of maintenance operations required in 5 million car-miles when the rate of correctable flaws is one per 13,920 miles (22,400 km) and the incidence of failures requiring replacement is 119,000 miles (191,500 km). To first-order, the increased cost of maintaining a closer tolerance is due to the increased number of wheel trueings required to bring wheel sets into match. The slight increases in the number of wheel sets removed and used may be neglected as being smaller than the accurancy of the model.

The average car mileage between wheel trueings is found to be

$$M = 13{,}770d^{0.163} \text{ miles}$$

where d = the policy maximum diameter difference in inches. Assuming annual car mileage of 40,000 (64,360 km) miles, the number of wheel trueings per car per year is

$$T = 2.9d^{-0.163} \text{ trueings.}$$

Each wheel set trueing is estimated to require 3.63 man-hours. At a fully loaded labor charge of $30 per hour, a wheel trueing costs $109 per axle set. Taking the diameter tolerance of 0.75 inches (19 mm) as baseline the additional annual cost per car for a closer tolerance is

$$\Delta c = 316d^{-0.163} - 331 \text{ dollars.}$$

The trade-off between capital cost of the propulsion system and the annual cost of wheel trueing may be made considering the present worth of the additional maintenance charges for a closer diameter tolerance. The present worth factor for a 30-year lifetime, at a discount rate of 10%, is 9.43. Exhibit 8 shows the present worth of the added maintenance cost with the extra cost of the propulsion system as influenced by wheel diameter policy tolerance. The crossover point comes at 0.15 inches (3.8 mm).

5.0 CONCLUSIONS

Wheel diameter differential does not significantly increase the total average motor loss during rail transit operation. Changes in motor power loss caused by wheel diameter differential during vehicle acceleration and deceleration tend to be compensating and to average-out over the trip profile.

Vehicle wheel diameter differential can increase the motor rating requirements in terms of overload for short time durations. Motor sizing should take into consideration the increased traction requirements imposed by wheel differential.

The annual cost of wheel servicing is increased by reducing the maximum wheel differential permitted by policy. The life cycle cost of the wheel servicing expense compared with the capital cost of the propulsion system, as influenced by the peak motor rating, favors a policy limit on wheel differential of 0.15 inches in the case studied.

EXHIBIT 1

VEHICLE TRACTION PARAMETERS

Vehicle Weight	130,000 lbs (loaded) (59,000 kg)
Acceleration (initial	2.5 mphps for 0 to 15 mph (1.12 m/s^2 for 0 to 24 km/h)
Deceleration	3.0 mphps for 50 to 1 mph (1.34 m/s^2 for 80 to 2 km/h)
(tappered)	2.3 mphps at 80 to 50 mph (1.03 m/s^2 at 129 to 80 km/h)
Vehicle Wheel Dia.	32.375" nominal (822 mm)
Vehicle Gear Ratio	5.087:1
Gear Efficiency	0.98

EXHIBIT 2

TRACTION MOTOR REQUIREMENTS WITH NOMINAL WHEEL DIAMETERS

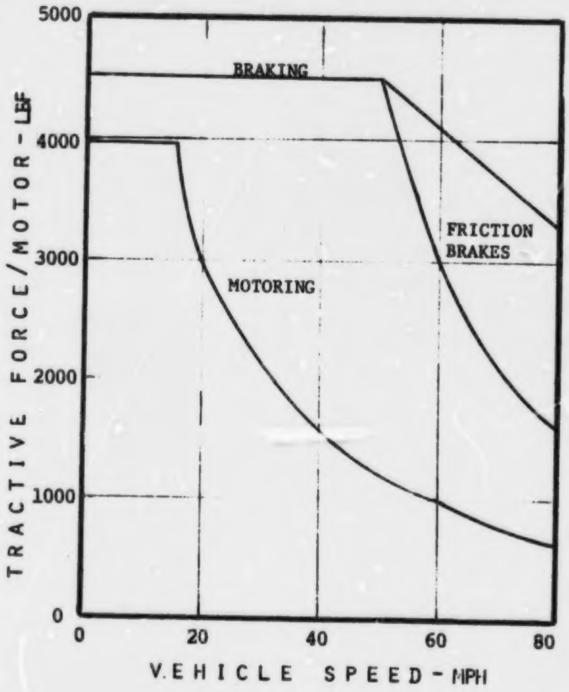
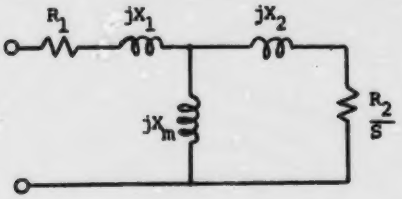


EXHIBIT 3
INDUCTION MOTOR MODEL



$R_1 = .069 \quad X_1 = .174 \quad X_m = 3.26$
$R_2 = .091 \quad X_2 = .174 \quad F = 50$ Hz

EXHIBIT 4
MOTOR LOSS WITH DIFFERENT WHEEL DIAMETERS

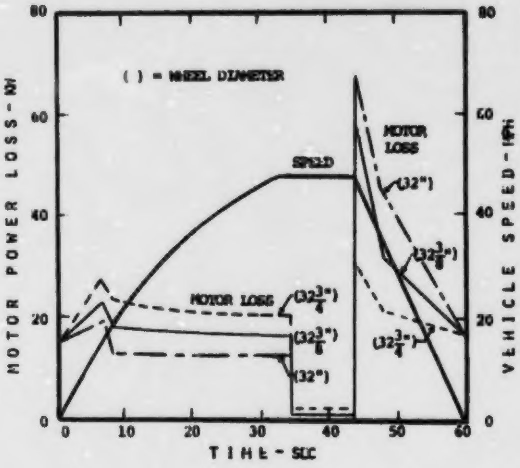


EXHIBIT 5
MOTOR LOSSES FOR 48 MPH TRANSIT PROFILE

Nominal Wheel Diameter*:	
Acceleration Energy Loss	630.3 kW-s
Cruise Energy Loss	7.0 kW-s
Deceleration Energy Loss	478.5 kW-s
Total =	1115.8 kW-s
Average Motor Power Loss** =	13.9 kW
Nominal Wheel Diameter + 0.375 Inch	
Acceleration Energy Loss	761.3 kW-s
Cruise Energy Loss	16.0 kW-s
Deceleration Energy Loss	346.8 kW-s
Total =	1124.1 kW-s
Average Motor Power Loss =	14.1 kW
Nominal Wheel Diameter - 0.375 Inch	
Acceleration Energy Loss	497.5 kW-s
Cruise Energy Loss	5.0 kW-s
Deceleration Energy Loss	611.8 kW-s
Total =	1114.3 kW-s
Average Motor Power Loss =	13.9 kW

* Nominal Wheel Diameter = 32.375 Inch (822 mm)

** Average motor loss based upon 80 second duty cycle, i.e., station dwell equal to 20 seconds.

EXHIBIT 6
MODEL FLOWCHART

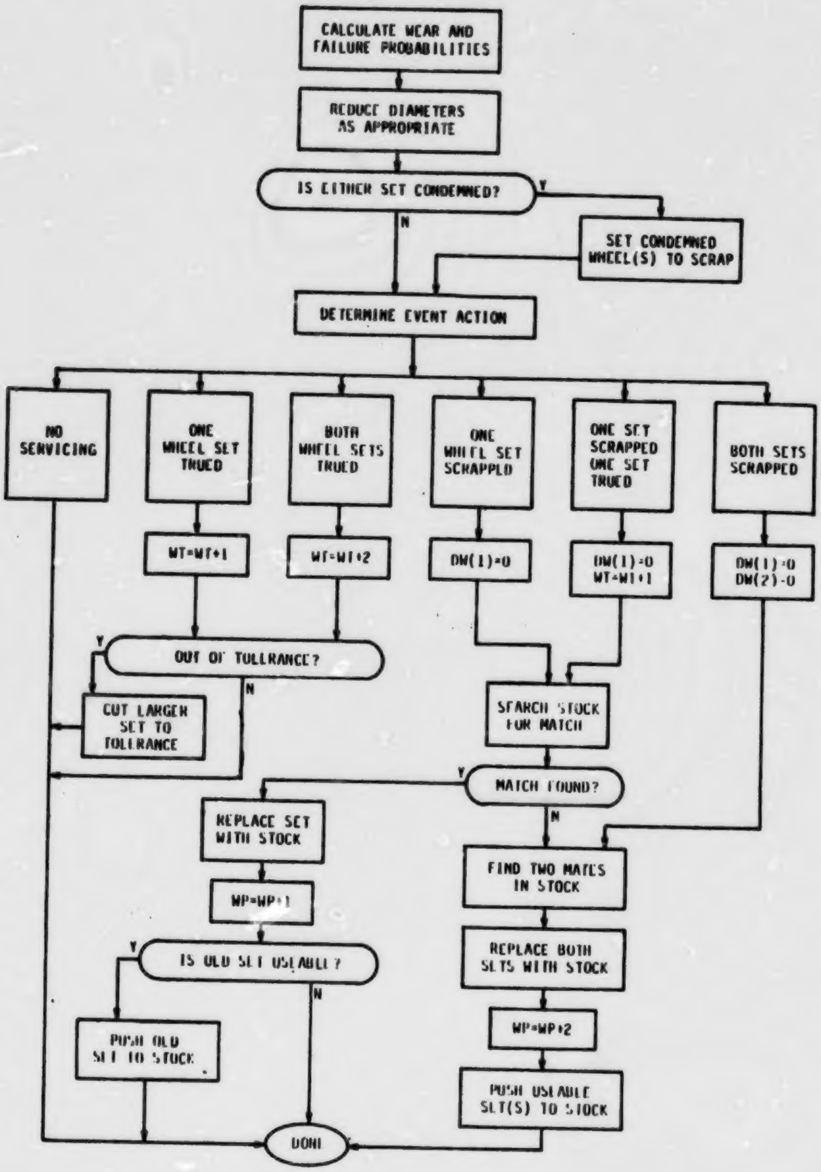

CALCULATE WEAR AND FAILURE PROBABILITIES
REDUCE DIAMETERS AS APPROPRIATE
IS EITHER SET CONDEMNED?
Y
N
SET CONDEMNED WHEEL(S) TO SCRAP
DETERMINE EVENT ACTION
NO SERVICING
ONE WHEEL SET TRUED
BOTH WHEEL SETS TRUED
ONE WHEEL SET SCRAPPED
ONE SET SCRAPPED ONE SET TRUED
BOTH SETS SCRAPPED
WT=WT+1
WT=WT+2
DW(1)=0
DW(1)=0 WT=WT+1
DW(1)=0 DW(2)=0
Y
OUT OF TOLLRANCE?
N
CUT LARGER SET TO TOLLRANCE
SEARCH STOCK FOR MATCH
Y
MATCH FOUND?
N
REPLACE SET WITH STOCK
WP=WP+1
FIND TWO MATES IN STOCK
Y
IS OLD SET USEABLE?
N
REPLACE BOTH SETS WITH STOCK
WP=WP+2
PUSH OLD SET TO STOCK
PUSH USEABLE SET(S) TO STOCK
DONE

EXHIBIT 7

WHEEL SERVICING OPERATIONS

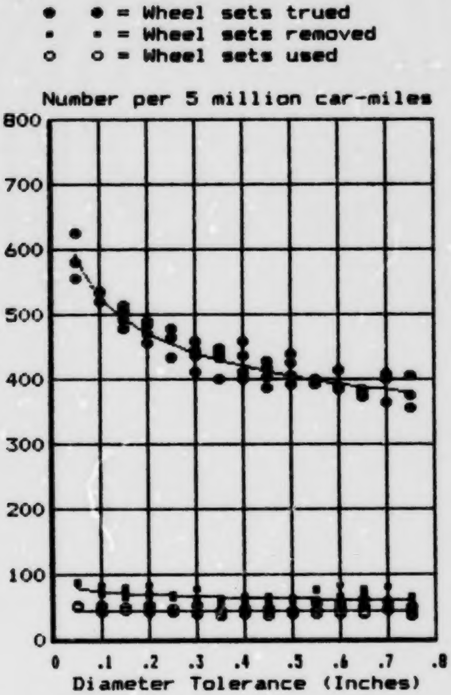
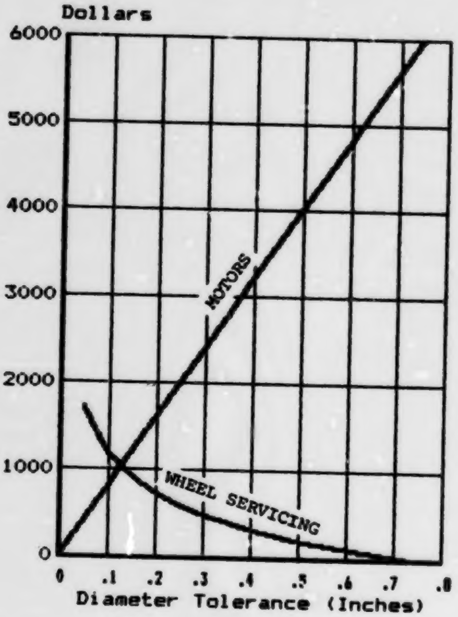


EXHIBIT 8

LIFE CYCLE COST COMPARISON



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POWER SEMICONDUCTOR DEVICES FOR TRANSIT APPLICATIONS

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Japan

Power semiconductor devices have been developed steadily and their applications area is spreading. Especially, gate turn-off thyristors (GTOs) have markedly increased in current and voltage ratings and have now entered into the practical applications stage, e.g. transit or other applications. This paper presents a brief view of present status and future trends for power semiconductor devices and comparisons between them for transit applications. Designs, structures, characteristics and basic application technologies are described for high power GTOs.

Introduction

Power semiconductor devices have been developed, though not as brilliantly as ICs and LSIs, but steadily. Now their applications area is spreading. Specifications demanded from users have become more and more varied. So, adding new trends (light triggering, self turn-off and integration etc.) to traditional trends (higher voltage, higher current and faster switching time), recent power semiconductor devices have higher performance levels and more varied functions. Design technology, using CAD, and semiconductor process technology making rapid progress, greatly contribute to realizing these requirements.

GTOs have been commercially available for up to 2.5kV-2kA and 4.5kV-2.4kA GTOs[1] are being readied for the market. GTOs have now entered into the practical applications stage as power transistors(P-TRs). GTOs have been replaced of fast switching thyristors, reverse conducting thyristors(RCTs), etc. in various equipment. For transit applications, VVVF inverter equipment for driving induction motors, chopper equipment for driving DC motors and CVCF inverter equipment for auxiliary power source using GTOs have been developed[2]. P-TRs have been used in chopper equipment for driving motors of battery powered electric vehicles[3].

This paper presents a brief view of present status and future trends for power semiconductor devices consisting of diodes, commutated turn-off thyristors, self turn-off thyristors, P-TRs and FETs. Then comparisons between power semiconductor devices for transit applications are presented. Finally, designs, structures, characteristics and basic application technologies are described for high power GTOs.

Present Status and Future Trends for Power Semiconductor Devices

Table 1 shows present status for power semiconductor devices.

3∿4kV-2.5∿3.5kA diodes are available on the market. Recently, fast recevery diodes have been developed and are available; 1∿4kV diodes are for free wheeling, and 10∿200V diodes for switching power supply.

Thyristors are increased in current, corresponding to the increase in Si single crystal diameter. One of the most remarkable technologies is resistivity control technology, using neutron irradiation[4,5]. This technology has greatly contributed to increasing in current and voltage ratings and improving characteristics since 1975. 4kV-3kA thyristors, using 4 inch diameter Si wafer, are available on the market.

Equipment using light triggering thyristors (LTTs) are excellent in electrical isolation and noise prevention capability. These advantages are shown especially for equipment using LTTs in series connection. The principal technological problem is to realize a sufficiently high light sensitive gate structure, preserving important characteristics, such as dv/dt characteristics and di/dt capability. To realize this goal, several kinds of light sensitive gate structures have been developed. 4∿6kV-1.2∿3kA LTTs are now available on the market and 8kV-1.2kA LTTs have been developed[6].

Reverse blocking fast switching thyristors with 1.2kV-1.5kA-15μs and 2.5kV-1kA-30μs ratings are commercially available using the new carrier lifetime control method.

RCTs can be improved in regard to their on-state and turn-off characteristics by adopting asymmetrical structure. 2.5kV-1kA/400A-30μs RCTs are commercially available and 2.5kV-800A/300A-10μs RCTs have been developed.

Gate assisted turn-off thyristors(GATTs) have turn-off time shortened with reverse gate bias during turn-off period. 1.2kV-400A-8μs GATTs are commercially available and 1.2kV-400A-4μs GATTs have been developed.

GTOs have markedly increased in regard to their current and voltage ratings. 2.5kV-2kA GTOs are now commercially available and 4.5kV-2.4kA GTOs are being readied for the market.

Althuogh, 4kV-2.2kA and 2.5kV-1kA static induction thyristors(SIThs: field controlled thyristors; FCTs) have been developed, high power SIThs are not yet commercially available because of the difficulty in their manufacture.

P-TRs decrease in handling current capability per unit area, as voltage rating increases. They have been considered that maximum voltage rating was in the 900∿1kV range. Recently, however, 1.2kV-300A P-TRs are commercially available and can be used in the 480V line.

Static induction transistors(SITs: J-FETs) and MOS-FETs have increased in the handling power and been added to the list of power semiconductor devices.

Figure 1 shows what power handling capabilities are expected to be available for the various device types at different switching frequencies[7].

Table 2 shows future trends for power semiconductor devices. Not only traditional trends (higher voltage, higher current and faster switching time) but also new trends(light triggering, self turn-off, module and integration) are now being examined.

For higher voltage, adopting an asymmetrical structure or self protectional turn-on function are also investigated. Increasing in handling current and light triggering for high voltage thyristors are actively being developed.

Fast switching and/or self turn-off bipolar devices will be devoted to improve switching characteristics. FETs will be devoted to increase in current and voltage ratings. Further, new devices, integrating bipolar function and MOS function and FET controlled optical switch are investigated.

Power semiconductor devices handling powers are increasing, their varieties are being extended and their characteristics improved. They have higher performances and more varied functions. So, power semiconductor devices will satisfy various applications areas.

Numerical analysis, using CAD, and rapid progress in semiconductor process technology greatly contribute to development and improvement in power semiconductor devices.

Comparisons between Power Semiconductor Devices for Transit Applications

Table 3 shows power semiconductor devices for transit applications. Thyristors and diodes are used in converter equipment for AC system rolling stock. For power factor improvement, converters with commutating circuits or those with added inverters are investigated for AC system rolling stock. For these equipment, RCTs and GTOs are used.

RCTs and GTOs are used in VVVF inverter equipment for driving induction motors and chopper equipment for driving DC motors for DC system rolling stock. RCTs and GTOs are also used in CVCF inverter equipment and DC-DC converter equipment for auxiliary power source on rolling stock. P-TRs have been used in chopper equipment for driving motors of battery powered electric vehicles.

Other devices such as SIThs will be used for transit applications, if they are available on the market, providing sufficiently high handling power for the purposes.

Because RCTs, GTOs and P-TRs are presently available on the market as power semiconductor devices for transit applications, comparisons between them are shown in Table 4. RCT handling power can easily be increased, but RCTs need a commutating circuit for turn-off. P-TR switching time can easily fasten but it is difficult to increase the voltage rating. GTOs do not need a commutating circuit and the handling power is easy to increase.

High Power GTOs

The use of GTOs, eliminating a commutating circuit, brings about many great advantages, such as weight and size reduction, efficiency improvement, low acoustic noise and highly reliable and easily maintainable equipment. GTOs have markedly increased in current and voltage ratings and have now entered into the practical applications stage. Figure 2 shows the progress in current and voltage ratings for high power GTOs since 1975[8].

The important basic design factors for high power GTOs were already mostly clarified, using the basic GTO structure, as shown Figure 3[8].

Basic design factors are VJ1/ρs control, N-base thickness control, αpnp and αnpn control and cathode emitter optimization. The first two factors are closely related to turn-off capability. The last two factors are mainly concerned with on-state and switching characteristics. Anode shorted emitter structure, pnn^-pn structure and buried gate structure with amplifying gate have also developed.

Figure 4 shows the exterior for commercially available 2.5kV-2kA GTO (SG2000EX21). Approximately 1,400 cathode emitter elements are arranged in 3 inch diameter wafer with the basic structure described above. Table 5 shows the major ratings and electrical characteristics for SG2000EX21. Root mean square current rating is up to 1000A. Figure 5 shows current and voltage wave forms during turn-off. Turn-off time is short as 17.5μs and turn-off gain is more than 6.5.

The gate circuit design involves one of the most important basic GTO application techniques. The gate circuit comprises on-gate circuit for turn-on, off-gate circuit for turn-off and reverse bias circuit, if necessary, to prevent dv/dt triggering. The on-gate circuit may be applicable to similar uses for conventional thyristors. The off-gate circuit, however, must supply a large current with a rapid diG/dt. The snubber circuit design involves another one of the most important basic application techniques. The snubber circuit must be designed to decrease transit voltage and switching power loss and to ensure turn-off.

Conclusion

Present status and future trends for power semiconductor devices and comparisons between them for transit applications have been presented. Finally, high power GTOs have been described. Higher performance and more varied functions are being achieved for power semiconductor devices. Satisfying the demands from users, their applications area is spreading more and more. Power semiconductor devices for transit applications, mainly GTOs, will be devoted to characteristics and mass production technology.

Acknowledgment

The authors wish to thank Mr. H. Ohashi, H. Takahara and N. Watanabe for useful discussions.

References

[1] T.Shinohe, et.al., International Power Electronics Conference, pp.75-86 (1983)
[2] T.Kanzaki, Toshiba Review, No.139, May-Jun, pp.30-35, (1982)
[3] S.Saeki, IEEE PESC Record, pp.274-281 (1975)
[4] H.M.Janus and O.Malmros, IEEE-Trans. Electron Devices, Vol. ED-23, pp.797-802 (1976)
[5] E.W.Haas and M.S.Schöller, ibid., Vol. ED-23, pp.803-805, (1976)
[6] H. Ohashi, et.al., to be published.
[7] M.S.Adler, et.al., IAS Annual Meeting 1980 pp.723-728
[8] M.Takeuchi and H.Ohashi, The Institution of Electrical Engineers, Power Division Colloquium, Professional Group Committee P6, (1983)

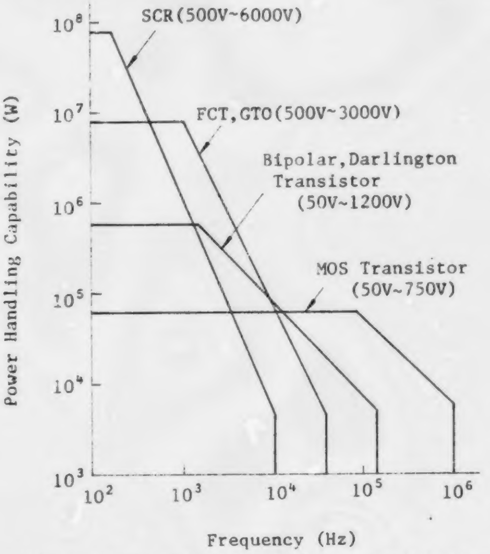


Fig. 1 Power switching devices capabilities by 1990 by device type and frequency[7]

Fig. 4 Exterior for SG2000EX21

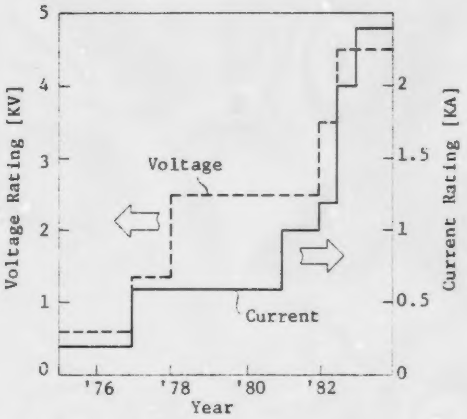
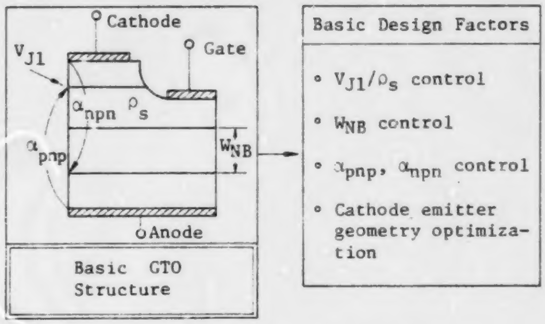


Fig. 2 Current and voltage rating progress for high power GTOs[8]



Cathode
Gate
V_{J1}
α_{npn}
ρ_s
α_{pnp}
W_{NB}
Anode
Basic GTO Structure
Basic Design Factors
V_{J1}/ρ_s control
W_{NB} control
α_{pnp}, α_{npn} control
Cathode emitter geometry optimization

Fig. 3 Basic structure and design factors for high power GTO[8]

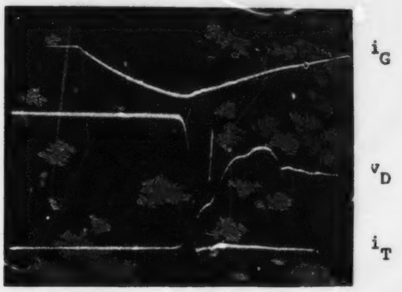


Fig. 5 Voltage and current wave forms during turn-off

v_D:500V/div., i_T:500A/div., v_G:200A/div., time:5μs/div.

Table 1 Present status for power semiconductor devices

Device		Voltage	Current	Switching Time*
Diode	General purpose diode	3000 V	3500 A	
		4000 V	2500 A	
	Fast switching diode	3000 V	1000 A	10 μs
		4000 V	700 A	10 μs
		200 V	30 A	60 ns
	Schottky barrier diode (SBD)	40 V	60 A	60 ns
		100 V	60 A	60 ns
Commutated turn-off thyristor	Reverse blocking phase control thyristor	4000 V	3000 A	400 μs
		6000 V	2500 A	
	Light triggering thyristor	4000 V	5 A	
		4000 V	3000 A	400 μs
		6000 V	1500 A	400 μs
		8000 V	1200 A	450 μs
	Reverse blocking fast switching thyristor	2500 V	400 A	30 μs
		1200 V	1500 A	15 μs
	Reverse conducting thyristor (RCT)	2500 V	1000 A / 400 A $(I_T)/(I_R)$	30 μs
		2500 V	800 A / 300 A $(I_T)/(I_R)$	15 μs
	Gate assisted turn-off thyristor (GATT)	1200 V	400 A	4 μs
	Triac	1200 V	300 A (I_{rms})	
Self turn-off thyristor	Gate turn-off thyristor (GTO)	4500 V	2400 A / 800 A $(I_{tgq})/(I_{rms})$	25 μs
	Static induction thyristor (SITh; Field controlled thyristor:FCT)	2500 V	**1000A (I_{tgq})**	**1.5μs**
		4000 V	**2200A (I_{tgq})**	3 μs
Power transistor (P-TR)	Single	400 V	40 A	6 μs
		400 V	250 A	9 μs
	Darlington	1000 V	400 A	20 μs
		1200 V	300 A	20 μs
	Gate associated transistor (GAT)	630 V	50 A	1.7 μs
		680 V	20 A	0.24 μs
Static induction transistor (SIT; J-FET)		1200 V	10 A	0.55 μs
MOSFET		250 V	30 A	0.3 μs
		500 V	10 A	0.5 μs
		1000 V	5 A	0.6 μs
GaAs-FET		150 V		5 ns

* : "Switching Time" means reverse recovery time for diodes and turn-off time for others

Table 2 Future trends for power semiconductor devices

Trend	Device	Technical Items for Realization
Higher voltage	Thyristor	Higher resistivity wafer
		Trade-off relation with on-state, turn-on and turn-off characteristics
		Asymmetrical structure
		Self turn-on function
Higher current	Thyristor	Larger diameter wafer
		Reduction in turn-on switching power loss
		Mounting and cooling technology
Light triggering	Thyristor	Direct triggering system and/or indirect triggering system
		High light triggering sensitivity with high dv/dt and high di/dt
		Higher output light emitting device, lower loss lightguide and higher light transmission system
Faster switching time	Fast switching thyristor	Life-time control
	GATT	
	FET	Higher voltage and higher current
Self turn-off	GTO	Faster switching time and lower switching power loss
	SITh (FCT)	
	P-TR	
	FET	High voltage and higher current
Module	Thyristor module	Lower thermal impedance
	Transistor module	
Integration	Triac	
	RCT	
	Darlington P-TR	
	MOS gate thyristor	
	FET-controlled optical switch	
	Insulated gate rectifier	
	MOS & bipolar connection	Cascade, cascode and parallel connection

Table 3 Power semiconductor devices for transit applications

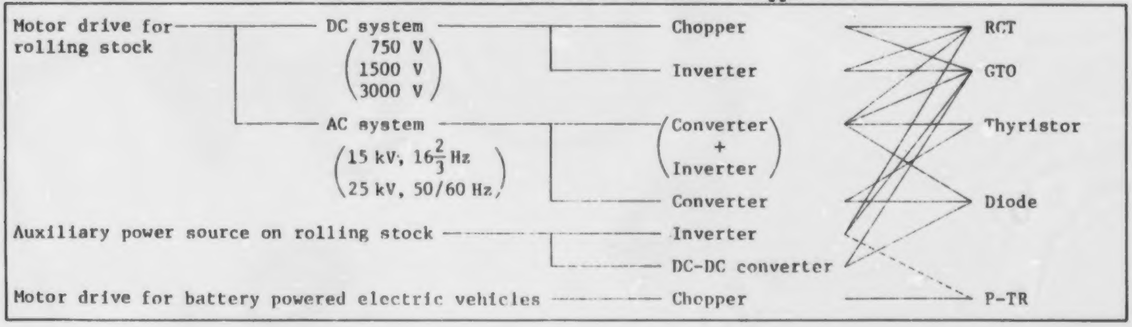

Motor drive for rolling stock
DC system
750 V
1500 V
3000 V
AC system
15 kV, $16\frac{2}{3}$ Hz
25 kV, 50/60 Hz
Auxiliary power source on rolling stock
Motor drive for battery powered electric vehicles
Chopper
Inverter
Converter + Inverter
Converter
Inverter
DC-DC converter
Chopper
RCT
GTO
Thyristor
Diode
P-TR

Table 4 Comparisons between power semiconductor devices for transit applications

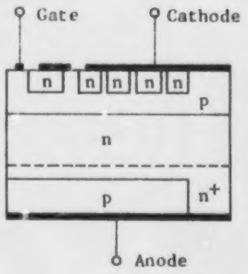
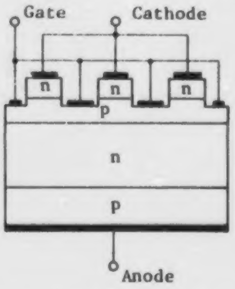
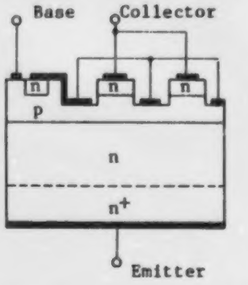
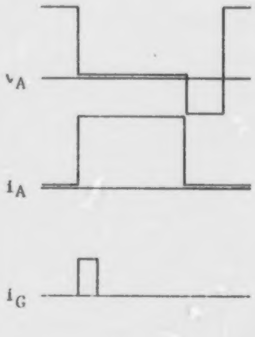
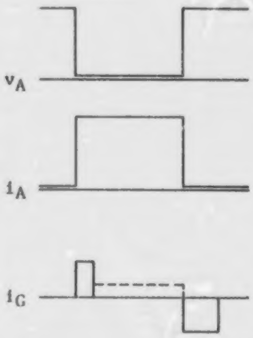
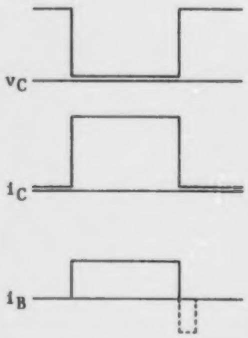
Device	RCT	GTO	P-TR
Structure			
Waveform			
Characteristics	Gate current for turn-on Commutation circuit necessary for turn-off Easy to achieve higher voltage and higher current	Gate current for turn-on Reverse gate current for turn-off Relatively easy to attain higher voltage, higher current and faster switching	Continuous base current for turn-on and on-state Zero or reverse base current for turn-off Easy to attain faster switching Difficult to attain higher voltage and higher current

Table 5 Major ratings and electrical characteristics for SG2000EX21

Item	Rating & Electrical Characteristics
Repetitive peak off-state voltage	2500 V
Peak turn-off current	2000 A
R.M.S. on-state current	1000 A
Peak on-state voltage	2.5 V @2000 A
Gate trigger voltage	1.0 V
Gate trigger current	1.5 A
Gate turn-on time	15 us
Gate turn-off time	25 µs

PANEL SESSION

"ADVANCED PROPULSION AT WHAT PRICE?"

Moderator: ***Peter Schmidt, Director of Systems Engineering, Baltimore, MTA***
Panel Members:
John Barber, Program Engineer, U.S. DOT/UMTA
Karl Dreiman, Deputy Manager of R&D for Railway & Road Traffic, AEG-Telefunken
Pierre Griffe, Chief Engineer, Paris Metro (RATP)
Peter Hartmann, Dornier System, GMBH
Hans Heider, Dir. Vehicles and Maintenance, Berlin metro (BVG)
Walter Kievel, Superintendent of Electric Vehicle Design, Chicago Transit Authority

As the title suggests, the topic of the panel will be issues of advanced propulsion deployment on new and existing rail transit systems. Since time is limited in related papers sessions, one purpose of this panel will be to provide additional time to answer specific questions as well as time for questions of a more general nature. In addition, panelists will have the opportunity to highlight their own experience and predictions for the future in this important area.

A number of issues complicate the transit operator's evaluation of ac drives versus dc choppers or more conventional switched resistor traction technology. Within each class, there exists a variety of propulsion control designs, packaging concepts and device technologies being exploited. Also operational experience varies and even when available is difficult to extrapolate to other installations.

This panel session provides a rare opportunity to raise major issues with experts experienced in advanced propulsion development and operations.

PETER SCHMIDT:

"Advanced Propulsion at What Price" which is a fairly aggressive title. I didn't make it up but given the title I thought maybe we could actually get down and generate a little controversy today about the use of this advanced propulsion equipment.

Everybody here at the conference is interested in it and 95% of us are probably proponents of it but maybe there is -- you can say a little bit about the other side of the issues as well, particularly from the operator's point of view. Can this equipment be operated, maintained, does it do what it says it's going to do and maybe we can do a little fortune telling a little bit further on -- future telling I should say as to when we might see some of this equipment in large orders at major systems.

The Panel members have largely changed from the ones that are in your book, so rather than give the changes, you have got the names of the panel members up here. I will introduce them briefly. Some of them wish to make -- or are prepared to make an opening statement about their experiences and position on a few things.

Let me start out with John Barber who is here as Special Assistant to the Associate Administrator for Technical Assistance of the Urban Mass Transit Administration, the federal agency which sponsors the R&D efforts in the United States and say a few words about the United States Government's position on advanced propulsion.

JOHN BARBER:

Thank you Peter.

Much of what we have been doing with the UMTA program has already been covered in the previous technical session. So, I will just spend a couple of minutes to underline what is the motivating rationale behind this program. Basically, what we are trying to do is provide a propulsion system for the transit operators in this country that is -- gives them a significant advantage in terms of reduced maintenance costs, in terms of increased reliability without incurring a significant capital cost penalty and it looks to us like the A.C. propulsion approach is probably the most productive way of achieving that end. That is the rationale behind our A.C. propulsion program that you have heard several presentations on during the last couple of days.

PETER SCHMIDT:

Representing the West German Federal Ministry of Research and Development, we have Peter Hartmann who is with Dornier. He is a member of the Advisory Group to the new transportation technologies advisory group to the West German Federal Ministry.

PETER HARTMANN:

Thank you Peter. As you know Peter, I have the honor to replace Dr. Bandel from the German Ministry of Research and Technology. He gives the best regards to this auditorium because of a very important governmental meeting, he wasn't able to join this party.

I will do my best to explain the position of the Ministry of Research and Technology in the question -- Advanced Propulsion at What Price?

Let's start with an overview of the BMFT policy and activities. Since around about 15 years we spent a lot of money in several advanced propulsion projects and so responded in the German propulsion industry.

I will bring your attention to the following projects. In the bus field the dual bus system, it means operation possibilities like diesel engine, electro motor, battery system, electric overhead wire systems, guided bus systems electrically and mechanically guided. Call bus systems for flexible operation and passengers demand. Projects in the cabin taxi or people mover field, the H-Bahn and M-Bahn projects in the light rail field, street cars, subway systems and commuter trains. Projects in the field of high speed inter-city transportation, new technologies in wheel and rail systems with speeds up to 150 miles per hour and magnetic levitations super speed trains with speed up to 250 miles per hour.

Most of these projects are now in a stage where operational tasks under the real public circumstances are in progress. They are ready for application in Germany and for the export market worldwide. These activities and the overall research and development program in the field of transportation of the Ministry of Research and Technology are created to fulfill the following requirements to make the public transportation acceptable and more attractive for all the people so that more people switch over from using their automobile for city tours into public transportation systems.

To minimize the investment costs and the operational costs to a reasonable value, to reduce the energy consumption, to reduce the space from the propulsion control system, to protect the resources and the environment, to optimize the maintenance costs, to increase the safety aspects and last but not least, to optimize the availability and reliability of the technical system.

Within these activities, advanced propulsion components were and will be sponsored by the Ministry like A.C./D.C. motor, chopper thyristor, GTO inverter and microprocessor controlled drive equipment, recharge battery drive systems and hydraulic drive systems, alternative fuels like methanol and hydrocarbon technology, synchronous and asynchronous linear induction motors and generators for recharging batteries and energy too.

So, you can imagine that the overall pallet of today's technical solutions and possibilities is carried out in the governmental program.

We arrived at a point where portable applications in different modes of advanced propulsions are or can be realized. The most important obstacles of application and implementation of advanced propulsion systems today are the financial problems of the government and the municipalities that the additional and conservative market on both sides, the manufacturers and the operators. The acceptability of new technologies by the politicians because all new things are connected with a risk.

So far, a vote for new technologies can be corresponded with failure. The way -- how decisions in this field will be started -- I remember George Pastor's opening speech that way and as indicated in the handout of this session -- advanced propulsion at what price - the price itself. The price on the other hands side depends through the number of production units. Thank you.

PETER SCHMIDT:

Albert Dzingelis who is on the program for New York Transit Authority which as most of you know is by far the largest user of rapid transit cars in the United States was unable to attend.

Walter Kievel from the Chicago Transit Authority, the second largest user, has kindly agreed to sit in on the panel to take the position of the more traditional large U.S. operator. Walter is Superintendent of Electric Vehicle Design for the CTA. He has been with CTA for 15 years involved in several recent car procurements. Walter.

WALTER KIEVEL:

As Pete already said, we are number two (2).

We only operate 1,200 cars as opposed to the some 7,000 in New York City. We have had the previous car order with Boeing Vertol. It included ten (10) advanced propulsion systems. Two (2) of them, only, were delivered unfortunately, due to cab signal interference and also low reliability of the equipment, they really never entered revenue service. But, we are still very much interested in the advanced propulsion systems though, as an established property with a very conservative management, we have many problems to -- in introducing A.C. drive or even choppers.

PETER SCHMIDT:

Thank you Walter. Mr. Okamatsu with Hitachi has already spoken here twice and is here representing the Osaka Metro which was unable to attend. I don't think we need a statement since we have already had his presentation on what is going on in Osaka and he will be available to answer questions about the state of advanced propulsion business in general in Japan.

Next is Pierre Griffe who is the Deputy Chief Engineer for Rail Research for Paris Metro. Mr. Griffe.

PIERRE GRIFFE:

As I said in my paper of the Rail Session II, we have now in Paris on the Metro, cars and chopper cars and about 1,200 chopper cars on the Regional Express Network and we will put into revenue service at the end of this year both on the metro and on the RER new microprocessor chopper cars.

Lastly, we have three (3) different A.C. traction prototype cars either in revenue service or running tests. This means that we have been making a very important and continuous effort in research and development of new drive systems.

When Mr. Frasco asked me to participate in this symposium, Transpac '84, I was very happy because I thought at last I am going to know what is the best solution in the world and when I come back home to Paris I shall stop a lot of different testing and concentrate all the efforts in only one direction.

Now the symposium is almost achieved. I don't have the best solution in the world. Why? Because I met during this symposium manufacturers and operators who all are very happy with the solutions they have developed. Let it be any type of chopper or any type of inverter. No solution has been abandoned and all solutions have been improvised.

I want to give you some examples and I apologize because I am not trying to mention all equipments. Our friends at Helsinki Metro are satisfied with the chopper with pulse width modulation inverter solution. Our friends of Osaka Metro are satisfied with the direct pulse width modulation inverter. Our friends from German Metro are satisfied with the current feed inverter. Our friends of Baltimore Metro are satisfied with the chopper. Our friends from Japan are satisfied with the GTO chopper, and myself too, I am satisfied. Yes. I am a little disappointed for not having found the best solution in Baltimore but I am happy to know that the tests which have been carried out in Paris are of use and will help improve the advanced propulsion system. Thank you.

PETER SCHMIDT:

Thank you. Our next panel member is Hans Heider who is a Director of Vehicles and Maintenance on the Berlin Metro. Mr. Heider.

HANS HEIDER:

Thank you. BVG is the largest transit authority in Germany with more than 14,000 employees. We are operating about 1,000 metro coaches and 230 old S-Bahn cars on a network of 125 kilometers and we have 1,500 buses on more than 1,000 kilometers of bus lines.

We started with testing of AC propulsion in 1976 with our first prototype twin car. The pre-production series of 12 cars is in revenue operation since about two (2) years.

The cars have run more than 1.4 million kilometers by now. We have decided to continue with A.C. propulsion. Our new series F-84 of 78 cars now under delivery as equipped with current impressed three phase system.

At starting the replacement of the 57 year old S-Bahn fleet the motor and car is under design. A.C. propulsion was decided here. In the field of new technology in interlocking, BVG is testing the SELTRAK system on one (1) metro line and an electronic interlocking of the SIMIS microcomputer system in one (1) metro station.

We further to note, new rapid transit systems, the 1.9 kilometer M-Bahn track is under construction. Commissioning and test operation will start autumn this year. This project is supported by the German Federal Ministry of Research and Development and senate of Berlin. It will be carried out by M-Bahn Co., AEG, SNV, and BVG.

It is my opinion that development and successful transfer of new technology into revenue service for attractive, reliable, and cost reducing operation can only be done by a long-term cooperation between supplying industry and transit authorities. Thank you.

PETER SCHMIDT:

The last panelist is Karl Dreimann, who is the Manager of Research and Development for the Railway and Road Traffic Division of AEG-Telefunken. Mr. Dreimann.

KARL DREIMANN:

I believe, that today development of new technologies has to aim at improving attractiveness and economy of our rapid transit systems and from the suppliers' point of view, we invest most of our efforts to transfer technology into products meeting these basic demands.

I would like to highlight some advanced technology. I think it could contribute to better riding comfort, better availability, reduced weight, reduced energy consumption, reduced maintenance.

I would like to just mention some things that we are doing at AEG-Telefunken in order to show how advanced equipment can improve those demands.

For example, chopper control with regenerated braking is giving better riding comfort, reducing energy consumption and reducing maintenance costs.

Three (3) phase propulsion systems are further reducing maintenance costs at the traction motors. We have developed both the current impressed and the voltage impressed systems in order to have available whatever may be the most suitable for the specific application.

Referring to components we are applying the GTO techniques for further reduced weight, reduced noise; freon cooling for once more reduced weight and reduced maintenance; optical fiber data transmission for EMI free train control for higher reliability; and new transport systems in which we take part in the development of maglev both the high speed systems of transrapid and the M-Bahn system for rapid transit having supplied for both the systems inverters of the propulsion system.

Development and especially prototype testing necessary to come to maturity of equipment ready for commercial application, costs a lot of time and money, but due to the long life time of our equipment, the initial investment is economic by terms of savings during that long year operation. So, I think the progress is worth working on and investing money in. Thank you.

PETER SCHMIDT:

Thank you. We have six (6) or eight (8) questions here which are not enough to fill up an hour. If anybody has any more questions, jot them down. I would appreciate it. I thought we might also try to do a little general discussion about what our panelists see as experts in their fields in Europe, Japan and the United States.

As we have said there have been a lot of -- there has not been an introduction particularly at the older properties in the United States with the chopper and the A.C. propulsion equipment. New York has got, oh, I guess it's over a thousand cars on order, all with cam. CTA is buying 600 cars with cam right now and maybe Walter could tell us a little bit about why they decided to stick with cams -- why the CTA as a property is not presently purchasing chopper equipment and what do they see in the future.

MR. KIEVEL:

The reason that the present order does not have choppers is simply because the testing with the prototypes for the previous order demonstrated the cab signal interference.

At the time the present order was undergoing the engineering phase and the spec preparation simultaneously with the testing of the chopper and so there was no hope -- even if a solution could be found to the cab signal interference -- that the specification could be prepared with chopper and go out for bid. So, there was a time problem involved in that. As it turned out, of course, the chopper interference with the cab signals would require an enormous modification to our way side equipment which of course is not included in the cost of new cars.

So, the chopper, at this time, and/or A.C. propulsion is on hold as far as CTA is concerned though we want to watch the developments around the world and on the STARS program to see what happens. What is the other part of the question?

Q. What do you see happening in the future?

A. In the future I think that A.C. propulsion is the way we want to go. The problem will be figuring out the cab signal difficulties and then implementing it. The implementation on the personnel side is one of our larger concerns as well. Due to money constraints as much as anything else, it's very difficult to pursuade management that they are going to have to hire 50 or 100 full-time technically qualified personnel to maintain solid state traction equipment when they don't have to, and by that they don't have to, if you buy existing switch resistance control. Also, since the federal operating subsidies are being gradually reduced and we are being forced to find more and more of our

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operating money locally, so it becomes an even greater problem to increase manpower to do something that is not there today. Especially since you are not substituting one type of person for another. You still have to have car mechanics to grease the couplers and change the third rail shoes and things of that sort and you also have to have technicians to maintain the electronic equipment. That's going to be, probably, the largest difficulty other than the cab signals for introducing any kind of static propulsion system in Chicago.

PETER SCHMIDT:

Thank you. Perhaps Mr. Okamatsu or one of his collegues would be willing to talk about what they see happening in Japan. Is there still cam equipment being produced in Japan? Will there be in ten (10) years? How about choppers? Are choppers passe now and in ten (10) years will there be choppers being utilized in Japan? Would you gentlemen be willing to comment on that? Let me just ask some specific questions.

Is there cam equipment still being produced in Japan for use in Japan -- switch resistor?

A. In Japan chopper controller now -- very much and very many transit operators use chopper controlling and now Osaka Transportation Bureau first decided to use VVVF inverter controlling and in the future I think VVVF inverter will be used by the other operators but I don't know how many operators will use this system because VVVF inverter is not proven and that -- the characteristics of maintenance costs is better than chopper controller no field data. So, I don't know how many operators will be using the VVVF inverter control system in the future.

PETER SCHMIDT:

Thank you. Mr. Griffe would you like to comment on what you see is happening in France and in Europe perhaps in the next ten (10) years, switch resistor versus chopper versus A.C.?

PIERRE GRIFFE:

Yes. In Paris and in France generally we have a great deal of choppers but it's difficult to throw out the solution which has given us satisfaction and which continues to be improved.

But, I think it would be reasonable for the Paris Metro to procure a small number of A.C. drives to allow us to be able to choose with a good technology of the best solution in the next '90s when we will be able to implement a new important renewal program of our rolling stock.

But, I am sure that our technical people will propose a solution before ten (10) years.

PETER SCHMIDT:

Thank you. Mr. Heider would you like to comment on what you think is going to be happening in Germany in ten (10) years?

HANS HEIDER:

Yes. In Germany we have a lot of series of cars with chopper equipment and we have some cars with A.C. equipment and I think that both solutions will be built in the future.

We at BVG have decided to go on with A.C. propulsion because we think that maintenance of the motors brings advantages. The advantage of energy consumption will be in both cases. We don't think that problems of the maintenance of these equipments will be so serious. We have trained personnel, electricians, and we are training the maintenance personnel in cooperation with the delivery firms and so we believe that the maintenance will make some problems but not too severe problems.

PETER SCHMIDT?

Thank you. Mr. Dreimann would you be interested in commenting as a supplier on what you will be selling the most of in ten (10) years?

KARL DREIMANN:

You see what I am going to sell is, of course, what fits best to the economics, the overall economics, of course, of the transit authorities and what we try, when introducing advanced technology, is to build up the infrastructure of the transit authority. That means to help authorities to live with the equipment in economic terms. That means training for example, giving all information necessary and giving especially the maintenance tools they need in order to be happy and to make economic benefit of advanced propulsion systems in operation.

PETER SCHMIDT:

Thank you. Why don't we get to the questions now. We will take the questions that have been submitted in writing first. I have a question for Peter Hartmann.

The question is from Eric Vogel, the general superintendent of car equipment maintenance for the Washington Metro, who is in the audience. What role does the German Federal Government play in funding and directing industry research activities and is this an active role or an inactive role?

PETER HARTMANN:

Well the policy of the Ministry of Research and Technology is a little bit in change. There is no active role to respond to the industry. It's a passive one.

PETER SCHMIDT:

Is there any Federal German money put in?

A: Yes, of course.

PETER SCHMIDT:

Eric do you want to amplify on your question any?

ERIC VOGEL:

No. I think it was basically answered but I was trying to establish some kind of relationship relative to the United States.

A: Well, I can give you some figures -- how much the Ministry of Research and Technology spends on this program on transportation overall. Its around about 120 million deutsch marks a year. It gives you an idea.

ERIC VOGEL:

Do you require research reports when things are completed?

A: No. That's not only for paperwork. We are building equipment. There are reports too; but you can see and test too.

ERIC VOGEL:

I guess there are a number of different schemes and there appears to be no concentrated effort on one or the other. Are you still playing around? We have heard over the last couple of days so many systems and technologies being tested and there appears to be no direct guidelines as to how one relates to the other.

A: Well, we have an overall program in the public transport as well as in the inter-city transportation. These are two (2) different things. Mass transport and inter-city transport and we started this program in 1969-1970 at which time we looked for different kinds of projects and now we concentrate on projects like a pyramid -- so far we found out that for the bus systems -- the buses themselves or new technology the dual bus and the guided bus, this will be a concentrated one.

We will not have concentration to the trolley bus systems themselves. On cabin taxis -- our Peoplemover system, we started three (3) projects in cabin taxi C-Bahn, the H-Bahn and the M-Bahn and after the research work now the H-Bahn -- the C-Bahn was cancelled two (2) years ago and the H-Bahn are in operation or starting operation as a testing project in the city of Dortmund and the M-Bahn will be built in the city of Berlin. The program is just in progress at this point. So, you can see that the Peoplemover system will stop or will end in the next three (3) or four (4) years -- and for the intercity systems, we are looking for high speed. This is what was mentioned for passengers' transportation and in this field we are looking for two (2) different kinds of technology. The standard conventional wheel on rail technology. This is a program we worked together with the Ministry of Research as well as the Ministry of Transport, as well as the Operator German Rail and there is a project building for a speed of 300 kilometers per hour. It's called the ICE intercity express of intercity Europe or whatever you can call it. It's like a TGV or something like that. A little bit modern in technology. This will start in operation the end of next year during the celebration of 150 years German railway and also we are looking for new technologies in the high speed area -- high speed 400 kilometers per hour -- contact free. This is the reason for using magnetic levitation systems.

We are looking also for -- we looked ten (10) years ago for different modes of levitation also air systems but we found out it makes no sense. The better way is go for levitation -- magnetic levitation systems.

In these parts we have different kinds of linear motors. You can use the short stator motor in the car. You need a power transmission. We are looking for long stator motors. It means that the motor is in the guide way themselves. There is no power transmission.

These are projects in progress. We built a test center. You learned about the Budd Company in yesterday's session and while this is run we look like the fox and the rabbit. What's better technology and when will we find it out, perhaps in 1985/1986? Then we decide what's going on with rail or magnetic levitation.

PETER SCHMIDT:

Thank you. Anytime any of the other panelists would like to comment on a question, please feel free to do so. Would anybody else like to comment on the role of their Federal Governments in funding R & D? John.

MR. BARBER:

Let me just add a couple of words about the United States Government. Our program is not quite as ambitious as the German approach. Basically we are concentrating on more in the neighborhood of what you might call incremental improvements -- short-term -- near-term, things where the results can be seen a little more quickly.

There are a few long-term programs that we are working on largely at the direction of the Congress. With respect to the particular concern here, A.C. propulsion, I guess the thing that is characterizing our approach is that what we are trying to provide is one (1) or two (2) or perhaps more marketable products available to the operators in this country which meet their needs. The way we have chosen to do that is to work with a couple of suppliers and a couple of contractors to produce the equipment. One of which is adopting technology that is existent in Europe and undergoing the modifications necessary to make it operable in this country and those are fairly extensive modifications.

The other contractor is developing, kind of from the ground up, a brand new system. We are close to the end of the developmental stage of that program and what we are starting to get ready for next will be an operational demonstration where we will take one (1) of those and operate it in some cars which we hope to get from New York City -- a couple of R44 cars to actually run the things around so you can look at it and see that the thing actually does run, it does work. We will be able to actually measure its characteristics -- its operating characteristics, energy consumption, determine its maintenance requirements and some estimate of the capital cost and then what we do is say to the operators and to the suppliers, okay you see a market, you see the technological advantages and the opportunities -- the operating advantages that such a technology could provide for you -- and then it's basically up to the operators to decide whether or not to go ahead with implementing the technology and then it's also up to the manufacturers to decide whether or not to provide it.

PETER SCHMIDT:

Thanks John. Let me get on to some of the more technical questions. We have two questions on wheels.

What is the European experience with wheel size matching and on three phase A.C. motor drives? Is it possible that remachining can be avoided all together and another question, how has the use of A.C. drives affected the wheel wear conditions and wheel life?

Who would like to take a shot at that?

Let me just say that one of the issues which may have come up is with the New York City standards for the U.S.D.O.T. program where they allow three-quarter inch difference in wheel size which is a major input to the design of the system. But let's get the European ...

MR. DREIMANN:

I would like to, at first, explain some basic information on this. Having three phase traction motors in parallel, on one common inverter, you have to look for balancing current to the traction motors which widely depends on the differences in speeds. That means on the differences of wheel diameter. But there is a designing tool to match reasonable requirements in wheel diameter difference of those axles being driven through one common inverter.

By designing the traction motor with some additional rotor resistance in order to allow speed differences without unbalancing the load too much. Practically, we design in between five to ten millimeters wheel diameter which we allow in between axles driven through a common inverter in order to get a compromise in between efficiency and maintenance questions.

The tendency of wheel diameters being in one car at parallel connection and one inverter is to stablize. That means the diameter being somewhat larger. It gets a bit more load. That means it has more tendency to slip. That means its getting a bit more wear on it. So, during operation the tendency is that the wheel diameters are equalizing.

But, of course, you have to look through and to prepare the maintenance according to the tolerable wheel diameter differences. That means, of course, that there is no unlimited difference in wheel diameter.

At Rapid Transit Vehicle the load during starting and during braking is referred one time to the motor with a larger diameter and at the other time with a motor with a smaller diameter of the wheel. So, during the duty cycle when starting and braking the thermal load on both traction motors -- or on all four traction motors being in parallel will be balanced.

So, there is very few over-rating necessary in case the tolerence is in between wheel diameter are limited to around about up to ten millimeters.

PETER SCHMIDT:

Anybody else care to comment on their experience with wheel life or wheel matching?

PIERRE GRIFFE:

Concerning the wheel's diameter, we do not replace or repair wheels because the difference between the wheel diameter is 5 or 10 millimeters. It is not a problem for maintenance of the cars.

PETER SCHMIDT:

What is a typical wheel mismatch that is allowed on a monomotor which already has to be matched fairly close? Does anybody have a good number?

Anybody in the audience have a good number?

MR. HEIDER:

The difference is about four millimeters.

Q: So a monomotor even puts more severe limitations on wheel size matching than would A.C. propulsion?

A: In Berlin we have two bogies. That means four axles and one inverter and the maximum acceptable difference is about seven millimeters.

The real wheel difference in cars in operation is not more than one millimeter and the wear is not bigger than in D.C. cars.

PETER SCHMIDT:

Okay. Let me move on to the next question which is "What amount of adhesion co-efficient is considered in the case of A.C. propulsion?" Who is the person that asked this question? Is he in the audience? To design with A.C. propulsion for different wheel sizes you have to assume some co-efficient of adhesion. Is that correct? Or are there any adhesion issues to be considered?

MR. DREIMANN:

The adhesion factor of course primarily does not depend on the propulsion technique you apply but it is controlled by fast response closed circuit loop control which is the most important factor.

But, three phase technology allows because of the natural characteristic of the traction motor to have a very fast tool in order to adjust the torque according to the physical adherence factor you have actually. That means with a three phase control there are realistically faster responses to slipping tendencies so that with a three phase control the tractive effort could be closer to the actual value of the adherence factor. This is not very important of course to rapid transit vehicles but it may be very important for locomotive operation.

PETER SCHMIDT:

Thank you. Next question. Many papers presented on three phase motor systems appear to make their comparisons with the old cam controller instead of the newer chopper system. Is this because they have doubts about whether the inverter system can compete with choppers on the same basis?

I would like a comparison between choppers and A.C. drive rather than A.C. drive and cam. Anybody care to take that one?

MR. GRIFFE:

That is always the problem. We must compare of the same solution and in the different papers compare the difference. But, I think it is very difficult to compare between the different networks. We try in the UITP committee which looks at the rolling stock and we try to compare the different solutions and the different networks and we have a lot of difficulties.

It's difficult to estimate the costs because of the differences -- in the different countries. The work conditions are different and we have real difficulty. But, we try to compare the different solutions.

In Paris, I believe we can do such comparison because we have chopper cars and we have, I hope in some years, a few series of inverters.

PETER SCHMIDT:

Anybody else like to take that one on? John.

JOHN BARBER:

It's true though it would be interesting to see some real in depth comparisons of the A.C. versus the chopper. I really haven't. I've done a few kind of off the cuff ones just for my own amusement. But, you sort of have to separate it into two parts.

There is first the control system and then there is the motor and what we do know is that the A.C. motor is significantly cheaper to manufacture than the D.C. motor and with the D.C. chopper you still have the D.C. motor.

The other part of the question then is the cost of the control system itself and that is a little harder to pin down, but it appears, on the basis of some of the studies we have done so far, and some of the information available to us that, in kind of a normal competitive situation, the total package price for a switch resistor D.C. or a chopper D.C. or an A.C. drive is probably going to be pretty close to the same.

One advantage of course that the chopper and the A.C. have over the switch resistor is that much of their price is a function of the price of the high power semi-conductors and that is an area right now where capabilities are improving extremely rapidly and the prices are dropping extremely rapidly so that over the long haul both of those two approaches are probably far ahead of the switch resistor D.C. in terms of price advantage.

In terms of performance, well, we do know that both the chopper control D.C. as well as the A.C. have the ability to regenerate power in varying levels of effectiveness but at least that does give you a way of comparing against the switch resistor D.C.

But, in general, I think it's true that we really don't have a good feel for much of a direct comparison between the two in real depth. Maybe over the next few years as more and more operators in this country and in other countries start experimenting and trying out the A.C. drives we will be able to assemble a better picture.

PETER SCHMIDT:

Thank you. Anybody else like to comment?

MR. HEIDER:

I think that in ten years both systems, chopper and A.C. propulsion, will exist. In Germany, it is today so, that A.C. equipment is heavier and dearer than the chopper equipment.

But I think that is a question of the development and if the development of GTO, freon cooling and so on is going on, the weight will be reduced and I think the cost will also be equalized and we think that maintenance of the motors and so on, in terms of reliability of the motors of -- A.C. motors is better than that -- of D.C. motors.

So that we think that higher rate is in A.C. development in the future.

PETER SCHMIDT:

Thank you. The next question was directed at Al Dzingelis from New York who is not here. The question is, "Since New York has not ordered choppers, have they been waiting for A.C. drive? Will New York specify A.C. drive for their next car buy if it proves out on their property?"

Well, I obviously can't answer for New York but let me take the opportunity. I think this ties in with the previous question which is a comparison of choppers and A.C. drive.

The APTA advisory board on which I sit, and so do many of the other property people that are advising the federal government on this R&D effort, is extremely interested in the A.C. drive project because of the motor situation. Many of our properties in this country do have problems with D.C. motors maintenance -- they are expensive motors and they are really looking less for a propulsion control solution than a motor solution and, of course, choppers are using essentially the same motors as are around anyway on the switch resistor control.

I believe that that is why New York is more interested in A.C. drive than they are in chopper. Their problem at the moment is motors more than anything else from a cost point of view and like other older properties, they are not in the position to take advantage of a lot of regeneration. They cannot permit the voltage to float up too high because they have a lot of incandescent light bulbs across the line. They have rotating machinery for power generation still in service and the rest of the system is not in a position to take good advantage of the energy savings but the motor maintenance is important.

Maybe Walter would comment on Chicago experience a little bit with motors and to see if you agree with me as to -- as the reason you said that A.C. drive is what you are looking at.

MR. KIEVEL:

Yes. It is primarily the motor maintenance problems that have directed us toward A.C. motors. We have had a tremendous amount of trouble with D.C. motors. In fact, APTA sponsored a winterization program which was directed, a lot of it, at traction motor problems -- was set up after the winter of '79 when I think every property had serious motor problems.

There has been a lot of work on it. But, the ultimate solution is obviously to get away from D.C. motors.

PETER SCHMIDT:

The next question also ties in. "Does the savings in D.C. motor maintenance really justify the A.C. drive complexity and has this been quantified?" Would one of our European or Japanese panelists like to comment on D.C. motor maintenance? I get the impression that D.C. motor maintenance is not the problem in Europe that it is in this country. It does seem to have the level of attention. Is that a fair statement? Is the theoretical advantage of the A.C. motor, the overriding thrust in developing the A.C. drive in Europe or in Japan? Anybody like to comment? Would you like to comment on the D.C. motor maintenance in Japan compared to A.C.? Is that the reason for pushing for A.C. drive -- for promoting A.C. drive in Japan? Is that what Osaka was looking for or the other Japanese properties? Would you like to comment on the French?

MR. GRIFFE:

Yes. In Paris our D.C. motors run about 600,000 kilometers between overhauls.

PETER SCHMIDT:

Now that's not -- a major maintenance cost is not in D.C. motors?

MR. GRIFFE:

We replace the brushes every 200,000 kilometers.

PETER SCHMIDT:

Would you like to comment on the Japanese position on D.C. motor maintenance?

Okay. Well, why don't we just move ahead. Can the panelists discuss their views on the various methods of cooling the solid state equipment, air, freon, oil, etc.? What looks like the advantages and disadvantages of the cooling techniques?

MR. DREIMANN:

On board the vehicle, the cooling is always finally to air. So, it is a question to make this transfer of losses from the semi-conductors with the lowest resistance possible. Air cooling is, of course, the cheapest way and the easiest way to do it because the air is directly taking the heat through the heat sinks from the semi-conductor element. But, there is one basic disadvantage with air cooling. That is dust and humidity accumulation inside the most sensitive part of the equipment which is the power part. So, by enclosing that equipment, we would get a reduction of maintenance costs. On the other hand, you have to look around for a method to make the thermal resistance as low as possible to come from the semi-conductor to the environmental cooling air and here freon cooling is optimum because it doesn't need any temperature difference for heat transfer. That means it has a maximum, the best thermal resistance possible. That means there is no temperature drop from the semi-conductor up to the surface of the vessel where, finally, there is a cooling to the air as the transfer of the heat to air takes place. That means we don't need any temperature drop for heat transfer but we use evaporation and condensation in order to take and to deliver the heat produced by the semi-conductor to the environmental air.

So, we feel that freon cooling will be the future solution on board vehicles.

MR. BARBER:

One of the critical aspects of the cooling is the fact that especially with semi-conductors, they are really vulnerable to overheating and they will tend to cook themselves and therefore the cooling system tends to become a weak link in the whole process.

To the extent that a cooling system requires some other active device like a pump or a fan or something of that sort, that injects into the system another point of vulnerability so that although you may be able to design fans and filters and things of that sort that do have a high reliability. In the past, that has often been a major source of problems with the operations here in this country and we sort of see that as a potential problem on out.

Therefore, any kind of a system whether it be a totally passive air system or freon cooling or anything else that does not require moving parts, would have an inherent advantage to the extent that you could actually design something that would work that way.

So, I guess, the underlying point is if you can eliminate the extra moving parts or the extra things that have to work -- the mechanical devices or whatever are the potential weak links in your cooling system, you are better off.

PETER SCHMIDT:

Thanks. Next question. "It seems the transit, like the rest of U.S. industry, is leaving the iron age and entering the silicon age. How will transit operators assure that their organizations develop the skills and knowledge to benefit from new high tech developments?" That sounds like an essay question on an exam.

PETER SCHMIDT:

Let me take a shot at that one since we have just solved that problem here in Baltimore. I believe that the issue of microprocessor control and maintenance in troubleshooting a microprocessor control is probably more difficult for us than the high power semi- conductors themselves. I think that certainly with choppers and certainly A.C. drive, one of the implications is that there will be microprocessor controlling and I think that we have to solve the problem anyway. That is not the only thing that is microprocessor controlled -- Washington's new cars have microprocessor controlled friction brake systems. We have microprocessor controlled destination signs. They are coming and they are inevitable but we like to believe that a lot of the reluctance of operators is our concern to get enough information on the programs and the troubleshooting on microprocessors. It used to be, when something went wrong, you could find the right relay or the right device and now if you don't have the program, you can't figure out what's going on quite often. Often the manufacturers are not interested in handing out the programs which they consider proprietary.

So, we are particularly concerned about getting proper diagnostic tools and in getting software information from the manufacturers of this equipment. As far as hiring, getting the skills and knowledge, that can be a real problem. We had an advantage since this is our first rail line and I believe that is some of the reason for the reluctance of the older operators. They are locked into certain union situations, certain skills and pay grades. We were locked into the pay grades of our bus division here which was the existing union contract. We created a new category of electronics technician because we knew we were going to have to solve this problem anyway, whether we have choppers or anything else. That is a slightly higher pay rate but it is difficult to spread the pay scales between different union employees, because union employees start at a certain percentage of their ultimate rate and work up for the first three years, so the electronic technicians we were trying to hire off the street, we were paying less per hour than the janitors that clean the stations. That is a real problem in attracting the right skills.

I think, however, we have been successful but I do believe that, from my point of view, it may just be a short-term problem until everybody is familiar with microprocessors. But those of us who are over 35 are a little afraid of them sometimes and there aren't that many people out there to hire to maintain. Would anybody else like to comment on the issue of maintenance skills?

MR. KIEVEL:

That's one of our largest concerns. We are virtually unable to offer salaries commensurate with the skill levels that are needed and until that situation is somehow altered we are in an extremely difficult position. We can't even hire technicians with competitive salaries for rail car design or any of the other areas within the CTA at the present time.

So, it is reflected throughout. Unless you are able to start a whole division or a whole group of people from the very beginning and get management to agree that you can offer competitive salaries within that new group, you are very much restricted on what you can do and the results are that you are almost unable to obtain the people that you really need.

PETER SCHMIDT:

There is a related question here. Maybe Walter would comment on. Has anybody considered the introduction of maintenance contracts for electronics control? Contracting the maintenance out rather than doing it in house?

MR. KIEVEL:

We have considered it but we haven't had the need to do it at the present time.

PETER SCHMIDT:

I think that some properties would find that they were running into trouble with their union agreements if they were to contract out a substantial part of work on maintenance.

MR. KIEVEL:

We have that problem with our motor maintenance. The electrical union in the shop objects very strenuously when we send traction motors out of the shop to be rebuilt. We have negotiated unofficial sorts of arrangements with them that we will try to do as much in house as possible. But, if it exceeds the workload, then we are free to send work out and it is always a question of who is watching whom today and whether we can sneak a couple more out and this sort of thing.

PETER SCHMIDT:

Would one of the gentlemen from Europe like to comment on the typical maintenance approach for this microprocessor electronics? Is it contracted out to suppliers or is it done by in-house staff?

MR. HEIDER:

No. It will be done by in-house staff. We have a staff of engineers and technicians who developed, together with the supply industry, the design and so they have a basic knowledge of these things. If the cars are in the workshops, the training goes on in collaboration with the suppliers.

We have a lot of skilled electricians and so on and they are trained for the new technologies and only in some cases, we give the cards and so on to the suppliers for repairing; most of the failures we make, we adjust ourselves.

PETER SCHMIDT:

Anybody else like to comment?

MR. GRIFFE:

We have somewhat the same policy. We have developed the new technology for many years and we have introduced progressively the new technology in our company. So, we have no problem with finding and paying the people.

PETER SCHMIDT:

I think that this issue of microprocessor maintenance is a two-edged sword. I think that the details are difficult for many of our people to understand but on the other hand it should be able to do self-diagnosis. We have heard a lot of that at this conference, that built-in diagnostics are practically free, except for the programming with microprocessor controls and you may not have to have but a few highly skilled technicians in a shop, and the equipment will essentially say what is wrong with it and the car house people can change the parts out and get the cars running. So, it may prove to be exactly the opposite of what we fear at the moment.

Which has better energy consumption, A.C. or chopper? I think that if we could have answered that at this conference we would have been in good shape.

MR. DREIMANN:

We did a lot of research regarding this question, having equipped chopper controls and A.C. controls on the same type of vehicles operating at the same lines.

And finally, there are no differences as well as in driving efficiency as well as in regenerated efficiency. In A.C. control you have somewhat more losses in the power electronic controls comparing with the chopper control because you have -- it's a current impressed system -- besides the chopper, the inverter part. It's a PWM inverter. You have a one-step control but the efficiency of the PWM inverter is less than the efficiency of a chopper. These additional losses of course are compensated by the better efficiency of the A.C. traction motor. The A.C. traction motor has an efficiency which is about three to four points better than the D.C. traction motor.

So, the overall efficiency of both systems is very close to the same. Regenerated efficiency, in the same way, is very close together. So, from the energy consumption standpoint of view, it makes very slow -- very small difference in between chopper control and three-phase control.

PETER SCHMIDT:

Thank you. I have a note here from Eric Vogel -- we were talking about traction motors -- to mention the interim report of the traction motor task force, APTA, has had a task force doing studies on premature motor failures and that report is available. I guess Eric, who is sitting over there, could arrange to get you a copy if you don't have one or don't know about it.

Want to say anything else about it?

ERIC VOGEL:

It's available from APTA.

PETER SCHMIDT:

Thanks. Mr. Duncan of the Ontario Ministry of Transportation Communications wants to discuss a question. Is he present?

A: I was just suggesting that the Japanese have found a way of turning sand into gold with all the new devices made of silicon. It looks like it could be quite profitable.

The thing that was concerning me here is that there is a tendency on many of the A.C. propulsion systems for them to mimic the series motor characteristics and this seems to me to be not exploiting fully the capabilities of an A.C. system. I plotted up here the typical speed time curves and the corresponding power time curve. The green one is a series motor characteristic which usually holds constant torque up to about a third of top speed, goes to constant power for a short duration and then follows the natural characteristics of the motor down.

Now the energy under this curve, in effect, is the kinetic energy required to take the vehicle up to top speed plus a little bit of drag energy. Now you can, of course, if you maintain a constant power characteristic, manage to enclose the same amount of energy under a much lower peak power. Now, if the peak power happens to be the driving force behind the capacity of all the power processing equipment upstream from the motor on board the vehicle into the substations and all the rest of it, then it would suggest that you are further ahead using a constant power characteristic such as we have here and I would like to know why -- it puzzles me why most of the presenters are using sort of a base speed ratio of nearly a half. Because it could as well drop down to about .2, I think.

MR. DREIMANN:

The reason why we need the highest possible tractive effort at low speeds is to have the fastest running time for a certain given distance in between stops. That means the faster your acceleration is, at low speeds, the shorter is your traveling time, especially in rapid transit operating profiles. That means you have to apply the maximum tractive effort to the maximum speed. That means the maximum rating for which you can economically design your equipment, which means cutting off your acceleration power at half the speed as we do it right now. That means that less than 25% of the maximum speed means losing a lot of traveling time.

PETER SCHMIDT:

Anybody else like to comment on the concept of high power -- high acceleration?

MR. DUNCAN:

I think I effectively dealt with that because I said the time it takes to get up to speed is the same from both respects. The area under the curve is the same.

MR. DREIMANN:

Yes. Okay. There is another very important aspect especially when having very short head time in between following trains. You have to accelerate at the station area as fast as possible to get the station free for the next train to enter it.

MR. KIEVEL:

And, of course, you are not getting to top speed. You never run a rapid transit car at top speed anyhow. You are only operating at about your quarter top speed as an average or even less than that.

PETER SCHMIDT:

I didn't completely understand the curve perhaps, but while I agree you get to the same velocity and you have the same energy stored in the vehicle. Your running time is still longer because it's taking you longer to get to that velocity. The general feeling is to get up to a lower speed quicker and require less kinetic energy. If the constant is running time, if you can accelerate as rapidly as adhesion permits and then coast to station, the first order energy is the lowest because the velocity is the lowest and kinetic energy is the lowest. So that the thrust is always to accelerate as quickly as possible and then running at the running time.

Here is an interesting question which is a little embarrassing for some of us. "Are there any properties in the United States which are financially self-sufficient?" And there is a little equation here that says the total operating expense is less than or equal to total revenues. I think the only one is the monorail at Disneyland probably.

Most transit operations, bus and rail, feel that they are doing a pretty good job if they hit 50% of their direct cost not counting their capital costs.

There are some rail properties which do better. I don't know what PATCO is running now, but they run a pretty high percentage. They don't quite make it. San Diego trolley which has just opened has done surprisingly well.

But, I would say that -- I can't think of any rail property which covers completely its operating costs out of the fare box.

How about the European situation? Is that basically true in Europe?

MR. HARTMANN:

In the Federal Republic of Germany there is no operator self-sufficiency. Nothing at all.

PETER SCHMIDT:

I really don't think there is any carrier of passengers who makes money except sometimes the airlines and that is even a question at the moment and that is only because they have a time advantage over the private automobile that none of the rest of us have. I -- except for special circumstances where automobile ownership is low, I can't think of anybody who does. Maybe somebody has an example.

Next question. "Maglev appears to be very attractive from many points of view. Why can't the governments and industries all over the world spend more effort on maglev than on conventional propulsion systems such as choppers and A.C.?"

Who would like to take that one?

MR. HARTMANN:

The Ministry of Research and Technology put not direct money into A.C., D.C., or whatever, chopper controlled, or GTO inverters in the propulsion system themselves. We give, sponsored money into projects which means into M-Bahn or wheel on rail technique or in dual buses.

Well, there is a philosophy in it because when you are looking in the policy of an industrial country, Germany is an industrial country, there is a share in work, a share in production and the share means transportation -- high transportation volume and high necessary safety and high availability and we are looking in the future -- the future of the next 50 or 100 years and we feel that passengers' ground transportation must be necessary. So far we are looking in high speed technology to replace the short distance air flight as well as try to move the modal split between private transportation -- means the automobile -- to the public transportation on intercity lines too and we find out that speed in European size of 400 kilometers makes sense. Now we are looking for technologies to realize such a kind of speed on the requirements on resources, and protecting the environment overall and so there is a philosophy of the Germans to put money in the maglev system.

PETER SCHMIDT:

Thanks.

MR. DREIMANN:

I would like to add some remarks. There are specific advantages with the maglev system which at first is that the forces are distributed not to just one point but over a longer stretch of the guideway and the vehicle itself. At second hand, there is no contact between the moving vehicle and the guideway, so there is no wear. That means no maintenance costs along the track and at third especially for rapid transit and during -- in rural -- in city areas as well as high speed transportation there is an advantage that because of having no rolling material on material -- no contact in between vehicle and the guideway these systems are very, very quiet which is especially important downtown as well as for the acceptability of high-speed passenger trains.

Q: You mentioned that -- which is true -- that you distributed the load on the longer section of track but, however, for high speed you need most likely the track will be elevated so you have to have columns and you have got to have the concentrated load on the ground anyway. So, it is the reverse of the train where you have the concentrated loads on the rail and you spread the load along the track.

Another thing also, I want to comment on, is on high speed maglev system, how much kilowatt may you use just to sustain the train? Because this is an important factor, too.

MR. HARTMANN:

This is not an important factor. I can give you a figure. You need one round about 100 watts per ton for the levitation and when you add it all together for a train we built, that Budd Company presented yesterday, it's run at about 120 tons with around about 110 kilowatts for levitation and you need about around 30 kilowatts for the air conditioning. It's a question -- and the other side, I want to point out once more, you are speaking about loads on bridges and when you make the dimension or the design of the bridge for a railway system you have point to point loads and this makes another calculation than area loads.

PETER SCHMIDT:

Well, I've run out of written questions and we have run out of time. Steve Barsony, our host, would like to make a statement since this is the last session.

STEVE BARSONY:

This will be very short. Thank you very much. I'm amazed with how many of you people are still here. On the third day these symposiums usually empty out. It must be showing that the interest is high in the subject matter.

I want to thank you for the host, especially Peter, and the tour that he will conduct in the afternoon. I want to thank the manufacturers, the properties, the foreign and the domestic suppliers who are here. I thank you for your papers and we plan that maybe our next session, rather than being in four years, since alot of new developments are occurring in this area, maybe we could have a meeting of this sort in a couple of years from now. I again appreciate all, all your work and that of Lou Frasco, Symposium Technical Advisor, and Ellen Witt, Conference Manager, who allowed this conference to go as smoothly as possible.

Thank you very much.

PETER SCHMIDT:

That concludes the last session. If there are any more questions, I'm sure the panelists will be glad to answer them after we break. Can we give one round of applause to the panel. (APPLAUSE). Thank you. We're adjourned.

Diesel Engine Improvements

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DEVELOPMENT AND APPLICATION OF THE CATERPILLAR 3500 SERIES ENGINES

John C. Hallinan and Alan E. Liffengren
Caterpillar Tractor Co.
USA

ABSTRACT

A new family of diesel engines - eight, twelve and sixteen cylinder Vees - has been developed by Caterpillar Tractor Co. Named the 3500 Series, these engines have a 170 mm (6.7 in.) bore, a 190 mm (7.5 in.) stroke and are rated at 74.6 KW (100 HP) per cylinder at 1800 rpm. They will be used for electric power generation as well as marine, industrial, locomotive, and off-highway truck applications. Some of the work required to meet the goals selected for this engine series is described in this paper.

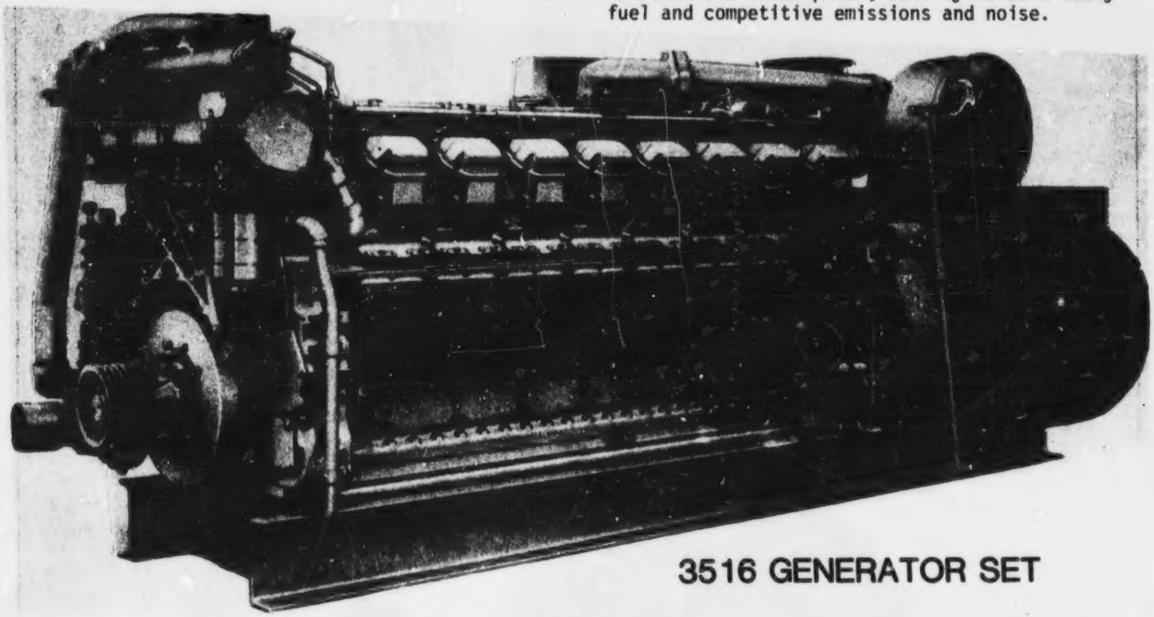
INTRODUCTION

During the early 1970's the need for more fuel efficient engines became apparent. Caterpillar's largest engines the D379, D398, D399; 159 mm (6.25 in.) bore, rated at 1200 and 1300 rpm and the D348, D349; 137 mm (5.4 in.) bore rated at 1800 and 2000 rpm needed to be replaced. These engines have been successfully applied for almost two decades in marine, industrial and locomotive applications as well as for electric power generation.

Design studies indicated that one design, 170 mm (6.7 in.) bore by 190 mm (7.5 in.) stroke, could replace both of the older models. This new line of engines, named the 3500 Series, like its predecessors uses the four stroke cycle and is turbocharged and aftercooled. However, unlike its predecessors, it has a direct injection combustion system rather than the older model's precombustion or indirect combustion systems. The initial ratings are 74.6 KW (100 HP) per cylinder at 1800 rpm and 63.4 KW (85 HP) at 1200 rpm. Eight, twelve and sixteen cylinder engines, all in a Vee configuration, have been developed.

OBJECTIVES

Because the 3500 Series engine had to be more fuel efficient than its predecessors, a goal of 222 grams/KW hr (.365 lbs/BHP hr) at 1800 rpm was selected for the first production ratings. Durability and reliability had to be equal to or better than the older models. A B50 life between major overhauls of 12,000 hours for the 1800 rpm rating and 20,000 hours for the 1200 rpm rating were chosen as durability goals. Other development objectives included good serviceability, low weight, growth capability, low lube oil consumption, ability to burn heavy fuel and competitive emissions and noise.



3516 GENERATOR SET

Some of the material in this paper has been presented in ASME paper 83-DGEP-2 at the ASME Diesel and Gas Engine Power Division Technical Conference in Peoria, Illinois on October 3, 1983.

	3508	3512	3516
BORE x STROKE MM (IN.)	170 x 190 (6.7 x 7.5)	170 x 190 (6.7 x 7.5)	170 x 190 (6.7 x 7.5)
DISPLACEMENT LITERS (CU. IN.)	34.5 (2105.4)	51.75 (3158.1)	69.0 (4210.8)
NET WEIGHT KG (LB)	4132 (9100)	5630 (12400)	6583 (14500)
RATING @ 1800 RPM KW (HP)	597 (800)	895 (1200)	1194 (1600)
@ 1200 RPM KW (HP)	496 (665)	746 (1000)	988 (1325)

TABLE I

DESIGN FEATURES

Figure 1 is a cross section that shows many of the design features of the engine. The Vee angle is 60°. Unique for current Caterpillar engines is the single head for each cylinder. Eight bolts clamp the head and the liner to the upper surface of the block. There is no counterbore for the liner. An aluminum spacer plate retains the seals for the lube oil and coolant, Figure 2. Each cylinder head has two intake valves, two exhaust valves and a hollow central post for the unit injector. Although used in other manufacturers' engines for a number of years, the unit injector is another unique feature for Caterpillar.

The cast aluminum piston has a cooling oil gallery supplied with lubricating oil from a jet. A second hole in the jet supplies oil for the piston pin and the underside of the piston crown.

A unique feature of the connecting rod is its slant bolt design. This allows the parting line between the rod and the cap to be placed in a more lightly loaded portion of the bearing. This design along with the stepped joint eliminates the need for serrations. The angled main bearing bolts serve to resist cap sliding without the use of side bolts.

There is an outboard camshaft for each bank of cylinders with three cam lobes for each cylinder. In addition to the cam lobes for actuating the intake and exhaust valves, the third cam lobe drives the unit injector.

In Figure 1, the air flow path may be traced from the turbocharger compressor, to the top of the aftercooler housing, down through the aftercooler core into the air plenum. This plenum is part of the block casting, a design similar to one that has been used in the Caterpillar 3400 Vee engines for a number of years (1). Air flows from the plenum through individual elbows to each cylinder head.

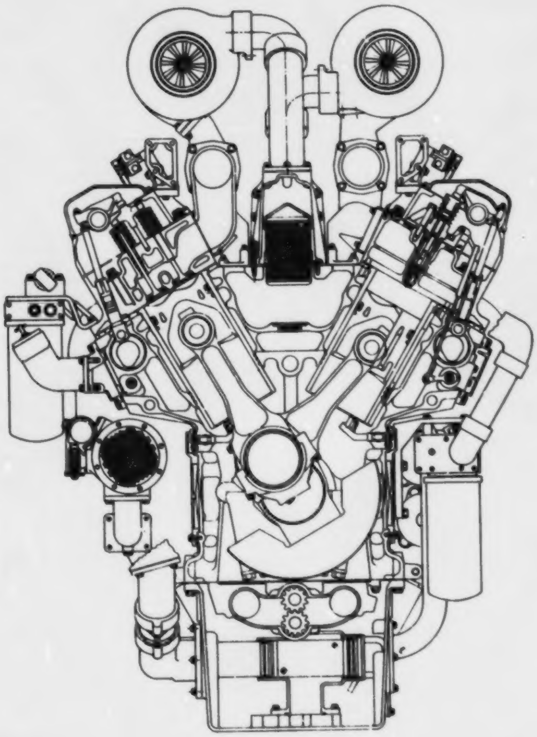


Fig. 1

Five lube oil passages extend the full length of the block, Figure 3. The largest in the center of the Vee beneath the water jacket supplies the main bearings which in turn supply the connecting rod bearings. The two lower passages, one for each bank, supply the piston cooling oil jets. A priority valve keeps oil from the cooling jet passages until the pressure in the large - main bearing - passage reaches 138 KPA (20 PSI). The two remaining passages, one for each bank, supply oil to the camshaft, cylinder head, valve train, turbocharger and gear train.

The coolant flow path may be followed in Figure 1. Coolant enters the block around the lower portion of the liner, flowing upward past the liner ledge, through the top deck of the block. Eight ferrules in the spacer plate direct the coolant into the cylinder head where it leaves at the upper corner. A manifold on each bank extending the length of the engine transmits the coolant to the regulator housing.

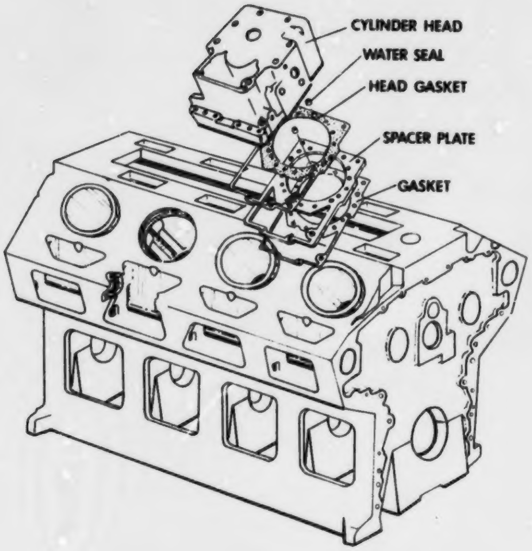

CYLINDER HEAD
WATER SEAL
HEAD GASKET
SPACER PLATE
GASKET

Fig. 2

The fuel supply pump provides fuel at 414 KPA (60 PSI) to the fuel headers - one for each bank - mounted adjacent to the coolant manifolds. Fuel for each cylinder is piped through a passage in the head to the unit injector. Return fuel reverses this path - flowing through another passage in the head then piped to the return header. To cool the unit injector approximately four times the fuel needed for combustion flows through the system.

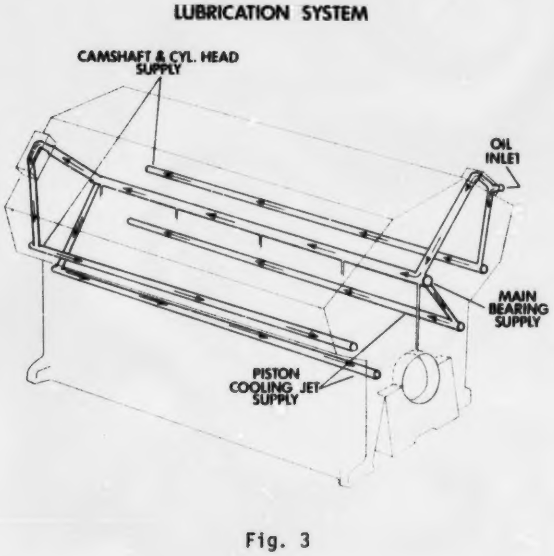

LUBRICATION SYSTEM
CAMSHAFT & CYL. HEAD SUPPLY
OIL INLET
MAIN BEARING SUPPLY
PISTON COOLING JET SUPPLY

Fig. 3

GEAR TRAINS

Gear trains are provided at both the front and the rear of the engine. The gears are nitrided alloy steel forgings. The front gear train drives the lube oil pump, the water pump and provides three accessory drive locations, Figure 4. At a crankshaft speed of 1800 rpm the remaining drive on the side with the water pump and oil pump can provide 131 KW (175 HP). The two drives on the other side can provide a total of 157 KW (210 HP). One of the upper drive locations, either right or left, is used to drive the governor. To maintain the same direction of rotation of the auxiliaries when the crankshaft rotation is reversed, the idler gear is meshed with the upper accessory drive gear rather than the lower gear for standard rotation, Figure 4.

The rear gear train, Figure 5, drives both camshafts. When required - such as an off-highway truck application - three auxiliary drives are provided on top of the flywheel housing. The total power output capability of the three shafts is 157 KW (210 HP) - all from one shaft or divided between two or all three as needed.

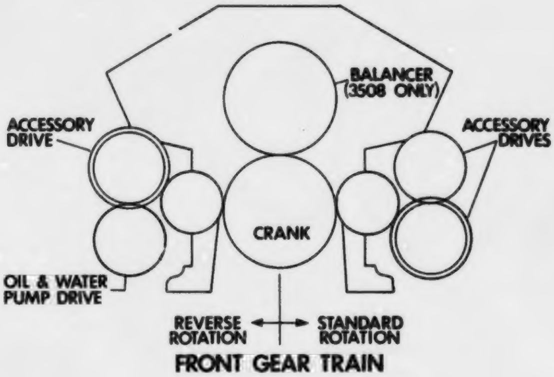

BALANCER (3508 ONLY)
ACCESSORY DRIVE
ACCESSORY DRIVES
CRANK
OIL & WATER PUMP DRIVE
REVERSE ROTATION
STANDARD ROTATION
FRONT GEAR TRAIN

Fig. 4

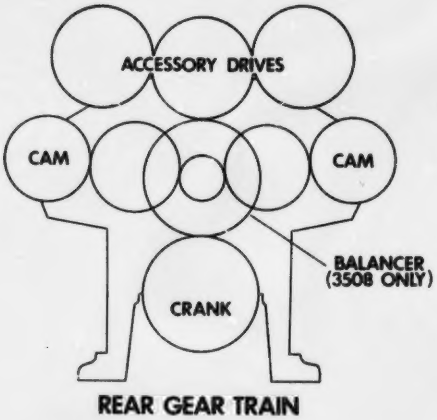

ACCESSORY DRIVES
CAM
CAM
BALANCER (3508 ONLY)
CRANK
REAR GEAR TRAIN

Fig. 5

Balance gears to compensate for primary unbalance are provided in both the front and rear gear trains for the 3508 engine.

PERFORMANCE, COMBUSTION AND FUEL INJECTION

A direct injection combustion system was selected to provide low fuel consumption. Like other Caterpillar engines, the first laboratory 3508 engine had a conventional in-line fuel pump mounted in the Vee. As engines get larger, in-line fuel pumps require longer fuel injection lines - almost two meters on the 3516 engine. Lines of this length would be especially undesirable with the higher fuel injection pressure needed with a direct injection quiescent combustion system. To shorten these high pressure lines, unit pumps mounted close to each cylinder were considered. A cam lobe at each cylinder would be required to drive its pump. With cams at this location, the next thought was to dispense with the high pressure injection lines and use unit injectors. Unit injectors allow the use of higher injection pressures - 110 MPa (16,000 PSI) - than normally found in a conventional pump and line system. As a result of these higher pressures, more efficient turbochargers and other combustion work the initial fuel consumption goal has been met or bettered for most ratings, Figure 6.

COMPONENT VALIDATION

The 3500 engines have been designed initially for 12.4 MPa (1800 PSI) peak cylinder pressure. Stress analysis techniques using both two and three dimensional finite element analysis have been useful in reducing the number of design iterations required to successfully validate components subject to cylinder pressure as well as those subject to inertia loading. Validation of these components was achieved by using either mechanical or hydraulic loading methods in accelerated fatigue tests.

In addition to the structural validation, bench tests were used to validate the valve train, the unit injector and its drive system as well as lube oil pumps and water pumps.

Space does not permit the discussion of the corrective action needed to resolve the problems uncovered with various components during the development program. They are discussed in detail in the original paper (2).

DEVELOPMENT HISTORY

After a study of various configurations, design work was started on the current bore and stroke engine - 170 mm (6.9 in.) by 190 mm (7.5 in.) - in 1972. Three two cylinder Vee engines started running in the laboratory in 1973, Figure 7. These engines have been quite useful in the piston, ring and liner development as well as for the initial combustion work. Subsequently, another 3502 was built solely for heavy fuel work (3). The cylinder blocks for the 3502 engines were also used for initial cylinder block structural evaluation.

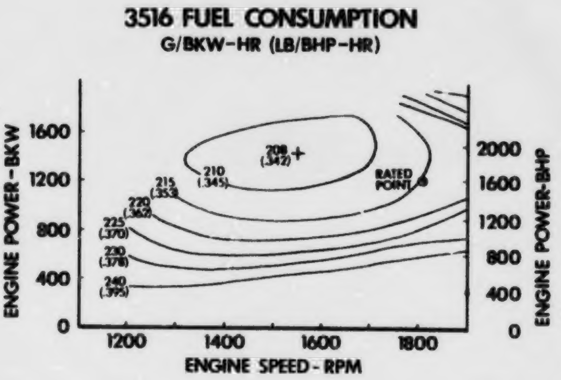


Fig. 6

The first eight cylinder engine ran in the laboratory in September 1974. A total of twenty-two engines were used for the initial development work. In addition to the three two cylinder engines, six 3508's, nine 3512's and four 3516's were built, Figure 7. Other engines were added later in the program for specific applications and for component work.

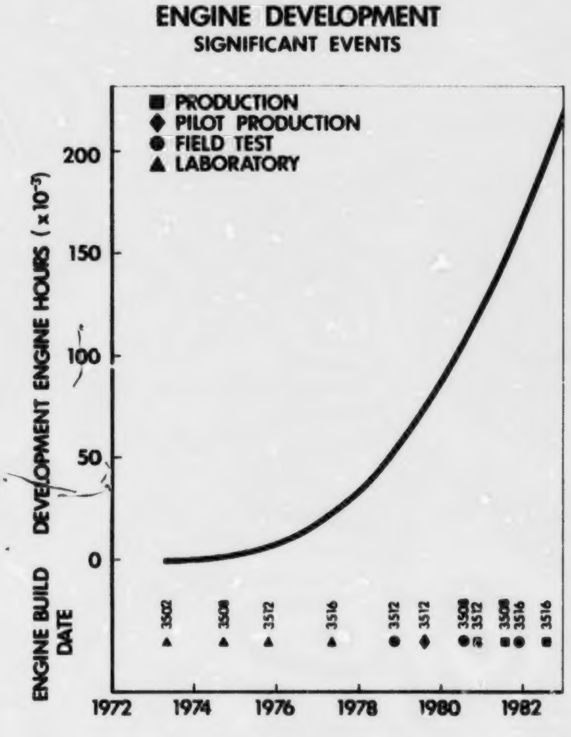


Fig. 7

As the twelve cylinder engine was to be the first in production, three 3512's were used for the first 3500 Series field tests, one each, in a mining truck, a towboat and a generator set. The truck and generator set engines were returned for examination after 12,000 hours. Inspection of the components of these engines was very encouraging indicating that the durability goal of 12,000 hours for the 1800 rpm ratings between major overhauls was reasonable. The marine engine in the towboat was replaced by a 3516 engine that is still in operation. Similar field tests are running for the 3508's and 3516's.

PILOT PRODUCTION

Twelve 3512 pilot production engines - four marine arrangements, two generator sets and six vehicular arrangements - were built starting in July 1979. By this time slightly over 80,000 hours had been accumulated on all laboratory and field test 3500 Series Engines - slightly over 34,000 hours on 3512's. The pilot production engines were built to allow the operations people - Manufacturing, Quality Control and Materials - to gain experience with the 3500 Series Engine as well as to do some market seeding. Approximately 54,000 hours were accumulated on the twelve engines with a maximum of 10,800 hours on one engine.

No major redesign to the basic engine was indicated by the pilot production experience. Tolerances on valve lifters and valve inserts had to be adjusted and a lube oil filter housing had to be redesigned to make it easier to clean.

LOCOMOTIVE APPLICATION

The 3500 Series Engines are well suited to meet worldwide locomotive needs in the 800 - 1600 HP classes. The power range, speed options, and excellent fuel consumption all contribute to acceptability to the locomotive applications. The capability to stop the engine, rather than require sustained periods of idling, provides additional fuel consumption improvement.

Fig. 8

A small space envelope and packaging flexibility with the 3500s further enhance the potential opportunity in locomotive applications. SAE standard and reverse rotation arrangements are available. Up to five gear driven auxiliary drives can be provided to drive accessory equipment. Adapters are available to mount both General Electric and Westinghouse generators while Kato and Brush have alternators that direct mount to the flywheel housing. Adaptability has been provided to use existing locomotive systems for engine cooling, traction motor blowers and 64V electrical systems.

GOVERNING & CONTROL

The standard Caterpillar hydromechanical speed governor can be used with an electric/air solenoid arrangement to provide 8 notch speed control governing.

The Woodward PGEV hydromechanical locomotive governor is available as an option on all 3500s. However, it limits the number of available auxiliary drives for accessory equipment.

Caterpillar has developed a micro-processor based electronic control that is being introduced as a locomotive speed/load control as its first application.

Its digital control logic will maintain the desired engine speed and generator excitation according to pre-programmed control strategies.

The control receives commands from the cab and signals from the locomotive, generator and engine to provide control to the engine fuel rack and generator exciter. The closed-loop feedback strategy is continually updating itself to compare the actual versus the desired conditions and provide correction as required.

Field tests were conducted on the electronic control in Grand Trunk Western Railroad's remanufactured Alco S4s (Figure 8) that were repowered with 670 kW (900 HP) Caterpillar D398 engines for switch engine service in Battle Creek, Michigan. These tests verified the control design to be capable of withstanding the environment in locomotive applications for temperature, vibration, G-loads, voltage spikes and electrical noise. Good performance characteristics were demonstrated that provided either quick or slow application of speed and load, depending on the operator's desires, with minimal wheel slip and exhaust smoke.

Significant improvements in productivity and fuel consumption are predicted with the sophisticated control strategies provided with this new electronic control.

LOCOMOTIVE INSTALLATIONS

The initial installations of the 3500s in locomotive service in North America are repowers of existing units.

The first installation is the repower of a Norfolk and Western EMD-GP9 with a 3512 rated at 895 kW (1200 HP) at 1800 RPM. A new Kato traction alternator was direct coupled to the engine using a common support rail as shown in Figure 9. This unit uses the new electronic control to provide full range speed and load control to optimize productivity and fuel economy in switching service. The locomotive was about ready for test trials at the time of publication.

The second unit is a 3508 rated at 375 kW (500 HP) at 1200 RPM repowering a 60 ton Baldwin locomotive as part of the locomotive modernization program sponsored by the Troop Support Command (TROSCOM) for the U.S. Army and Air Force. The engine generator package, shown in Figure 10, is pre-aligned and mounted on support rails for ease of mounting to the locomotive bed plate. This unit used the standard Caterpillar hydromechanical governor with electric/air solenoids to provide notch speed control. The initial unit was being completed for test trials at the time of publication.

A third installation is for two new European built Babcock & Wilcox locomotives for Ensidesa steel mill in Spain using the 3516 rated at 1194 kW (1600 HP) at 1800 RPM. These units use the Woodward PGEV locomotive governor and Brush traction alternators. The engines were being shipped at the time of publication.

These three initial locomotive applications of the new Caterpillar 3500 Series Engines will be placed in service in late 1983 and early 1984. It is anticipated that the claims for improved fuel economy and productivity will be verified in actual service.

PRODUCTION

Production for the 3512 engines started in July 1980, for the 3508's in July 1981 and for the 3516's in July 1982. As of November 1983 approximately 1100 engines had been manufactured.

In summary, the 3500 Series Engines have met the goals that can be measured at this early stage of their life. Improved fuel consumption, serviceability and lube oil consumption have been established. Reliability and durability will take time to acquire a good statistical sample. Initial reports are encouraging and it appears that the 3500 Series Engines will be a worthy successor to the older models.

Fig. 9

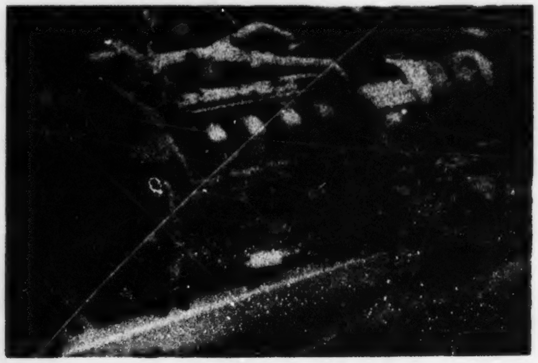


Fig. 10

REFERENCES

(1) E. J. Kirk and D. R. Krull - Caterpillar 3400 Series Engines" - SAE Paper 740038 (1974)

(2) J. C. Hallinan - "Development of the Caterpillar 3500 Series Engines" - ASME Paper 83-DGEP-2 (1983)

(3) B. G. Richards - "Caterpillar Residual Fuel Test Program" - ASME Paper 83-DGEP-1 (1983)

POWER PLANT OPTIMIZATION FOR FUEL ECONOMY, EXHAUST GAS EMISSIONS, SOUND LEVEL, ROAD SAFETY, AND RELIABILITY

Bengt Palmer
Saab-Scanai AB, Scania Division
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The Scania Bus Division of Saab-Scania of America, Inc. will start manufacturing buses in the USA during 1984. But Scania has actually been designing and manufacturing buses in Sweden since the beginning of the century. Since the engine and transmission are of particular importance to fuel economy, especially with present day fuel prices, Scania has devoted determined work towards optimizing the various components of the driveline. We carry out in-house all of the development, design, testing and production of all components of the driveline, and we have therefore achieved unique coordination of the various units.

The Saab-Scania group specializes in transportation technology. Our exports of trucks above 16 metric tons GVW represent more than 15% of the total world exports of diesel-powered trucks. Most of our trucks are turbocharged. Saab was the world's first car manufacturer to launch a turbocharged sedan. Two out of every three cars we manufacture are exported, primarily to the USA and Western Europe. Moreover, Saab-Scania is a member of the group of companies that belongs to the exclusive "fraternity" of advanced military aircraft manufacturers. Aircraft such as the Tunnan, Lansen, Draken and Viggen have all aroused international interest, and so has the latest Gripen. We have now also established ourselves on the civilian aircraft market by producing the Saab-Fairchild 340 -- an airliner for the rapidly growing regional traffic. This outline of our product range demonstrates that we have devoted ourselves exclusively to products in which efficiency, engineering precision and reliability are vital features.

We are also well established as a bus manufacturer. Our buses are now in service in Scandinavia, Europe, Iraq, Africa, Australia, Brazil and Argentina. And they have also been operating for some time in the USA on a trial basis. Conventional two-axle as well as articulated buses are being tested, and both types have aroused keen interest.

Far-Sighted Development Work Produces an Advanced Diesel Engine

At Scania, we have long taken it for granted that modern buses should be diesel powered. Our present low-speed, turbocharged diesel engine powering all Scania buses today proves that our conviction was correct. A characteristic feature of this engine is its low fuel consumption.

Our efficient diesel engines of today are the result of many years of research and development. Our work in this field started way back in the beginning of this century. Scania-Vabis presented its first diesel engine in the 1930s. It was a precombustion-chamber design with a swept volume of 7.75 litres and a rating of 120 hp at 2,000 rpm.

This first engine promised success and spurred us on to further development work. The orientation after World War II was towards supercharged, direct-injection engines. And the work produced results. In 1951, we caused a sensation by starting serial production of an 8-cylinder, in-line, direct-injection engine. It appeared obvious that we were in the right direction. So we carried on with our development work and, in 1958, we launched the first diesel engine designed specifically for turbocharging. We considered that this engine would provide excellent opportunities for further development towards gradually increasing output while decreasing fuel consumption.

One of the features that enabled us to achieve this goal was a thoroughly tested system for optimized mixing and distribution of the fuel/air charge. Scania has collaborated in the development of an injection pump that gives increased injection pressure and provides improved distribution of the fuel. This has resulted in very efficient combustion, at the same time reducing the smoke emission. The opportunity was also available for reducing the sound level and the exhaust gas emissions, in pace with the increasingly strict environmental demands.

As compared to the bus engine, the truck engine must be capable of withstanding appreciably higher strains. This fact has been of great benefit to us. Due to the large number of trucks we produce, every modification to the engine design was first tested on our trucks under very severe operating conditions. So the components of the Scania bus have been proved by long and arduous practical tests to correspond to the Company's demands on quality, economy and reliability.

The Low-Speed Engine Philosophy Benefits Fuel Economy

The present day prices of diesel fuel demonstrate that our efforts to reduce the fuel consumption have been far-sighted. A decrease by 8% since 1962 may perhaps appear insignificant. But this value refers to the specific fuel consumption at the optimum point of the engine power curve. The difference in reality is appreciably greater. Assume that a power of 162 kW is necessary for a bus to negotiate a certain gradient at a certain road speed. Yesterday's bus engine must run at the full speed of 2,200 r/min and at full power, and will then consume 245 grams of fuel per kWH. With today's engine, the bus will negotiate the same gradient at an engine speed of 1,600 r/min and only 85% of the full power will be utilized. The overall result is that the fuel consumption will be reduced by 20% or 10 litres per 100 km.

This alone is sufficient to explain why Scania buses in introductory tests in U.S. city traffic have been proved to consume between 15% and 20% less fuel than other buses operating under similar conditions. Let us now consider the Scania low-speed engine philosophy that we have adopted to drive our buses. This philosophy is illustrated by the diagram shown in Figure 1. The horizontal line represents the normal torque developed by the engine at different speeds. The most economical engine speed can be selected by adapting the total ratio of the transmission and rear axle. As illustrated by the graph, the fuel consumption is a minimum at relatively low engine speeds. However, to enable the engine to be run at a speed at which the fuel consumption is a minimum, the rating of the engine must be higher than the power normally utilized for driving the bus.

But good economy is not merely a matter of reducing the fuel consumption. Economy is also affected by the reliability and useful life of the engine. The Scania low-speed engine philosophy is also of benefit in this respect, since a lower engine speed obviously results in a corresponding reduction in wear.

The Scania Bus is Silent

A bus used in mass transit must be silent — on the inside for the passengers' sake and on the outside for outside for the environment's sake. At 71 dB the Scania CN112 is extremely silent. This is due to many factors, one of which is the low engine speed.

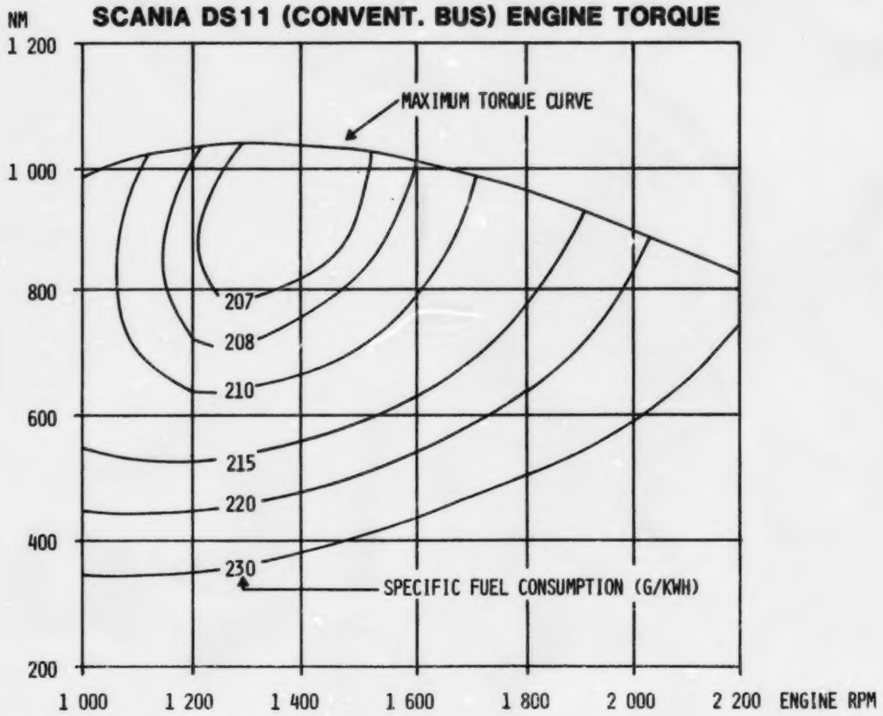


Figure 1 — SCANIA'S LOW-SPEED ENGINE PHILOSOPHY: Fuel consumption is lowest at relatively low speeds.

The bus engine must therefore be so powerful that it delivers sufficient power for driving the bus even when it is running at the low -- and thus economical — speed. Well-developed turbocharging is one of the features that have enabled Scania to develop the engine further so that is corresponds to this demand, without the need for increasing the overall dimensions of the engine.

One advantage of using a small turbocharged engine is that the friction losses of such a small engine are less than for a larger naturally-aspirated engine.

Another reason is the low stalling speed of our automatic transmission, so that the driver cannot rev up the engine when pulling away.

The third reason is the location of the engine at the extreme rear, where good opportunities are available for efficient insulation, without restricting the accessibility. We have obviously used this opportunity. The thermostatically-controlled, low-speed radiator fan is located separately from the engine compartment and this has also contributed to the low noise level. But the noise emitted by a vehicle consists of several different sources of sound. So we have endeavored to reduce each individual source, so that it will give the minimum possible contribution to the overall noise level. Figure 2 shows the most important measures we have adopted, with the result that the noise emitted by the Scania bus is almost 10 dB below that emitted by most other buses.

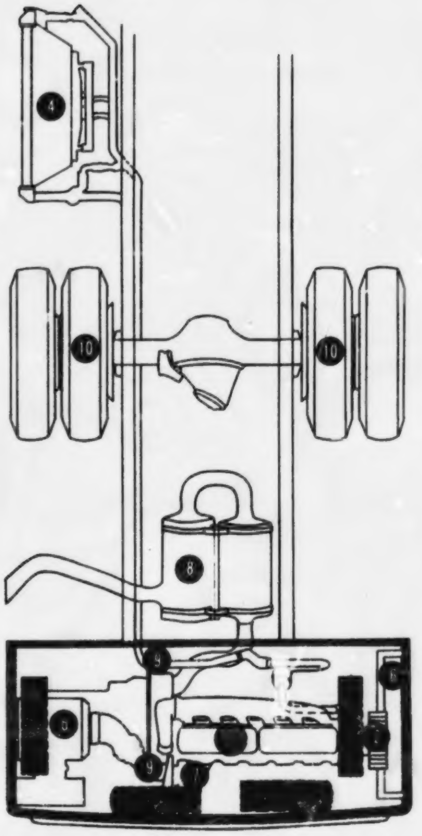


Figure 2 — **THE SILENT BUS: This diagram shows the principle noise suppression points on the Scania bus.**

Also as an Articulated Bus

The Scania CN112 chassis is employed for most types of city buses, such as single-deckers, double-deckers and articulated buses. The Scania CN112A is the designation of the articulated bus now being demonstrated in the U.S.

The Scania CN112A has a "pusher" engine, i.e., the engine and transmission are located behind the third axle of the bus. These propulsion components are the same as those used for the two-axle bus, and this obviously facilitates the stock of spare parts and facilitates service training, etc.

The articulated bus is designed and built so that the chassis weight distribution (positive downward force applied by the rear section onto the center of the fifth wheel) and the main dimensions (wheelbase, overhang and the distance between the center axle and fifth wheel center) minimize the risk of jackknifing. No special articulated-joint control systems are therefore necessary under normal road conditions.

However, an automatic articulated-joint control system, developed by Scania and designed to prevent the bus from jackknifing inwards towards the center of the curve or outwards by the rear section breaking away, is provided for exceptional situations. The articulated joint is equipped with a pair of hydraulic dampers which effectively arrest excessive movements of the articulated joint at higher speeds.

The accelerator control is electrical and is connected to an electronic control unit that continuously receives information on the articulated joint angle. The electronic control unit automatically reduces the accelerator setting in three steps, as the angle of the articulated joint increases. At low road speeds — below 10 km/h or 6 mph -- the system is inoperative and the bus then has normal tractive and pulling-away power, regardless of the angle of the articulated joint.

The above measures have been adopted to eliminate the risk of jackknifing.

Another electronic system is connected to the driven axle of the vehicle. The speed of this axle is recorded and is compared with the speed of rotation of the center axle of the bus. If the speeds of the two axles do not coincide, a disc brake in the articulated joint will be applied and the two sections of the bus will thus be locked in relation to one another. At the same time, the accelerator setting will be reduced and the driven wheels will be prevented from spinning. The disc brake will be disengaged as soon as the speeds of the two axles coincide again. The accelerator setting will then revert to the normal position.

If the brakes are applied heavily, thus giving rise to the risk of the wheels locking, the disc brake will be applied and will prevent jackknifing or break-away of the rear section.

This feature of the articulated-joint control system is designed to prevent skidding of the bus.

If the angle of the articulated joint should become too large, the driver will be warned by an audible and visual alarm. If the articulated-joint angle should become larger than the angle considered safe when the bus is being reversed, the accelerator setting will automatically be reduced and the brakes will be applied on both rear axles of the bus.

Low Exhaust Gas Emissions

Authorities throughout the world are making increasingly stringent demands on reduced exhaust gas emission values. Our well-developed engine design ensures that emission levels conform to the U.S. Federal regulations, at the same time as the engine has good fuel economy and the exhaust smoke is hardly visible. The table shows the emission levels of the Scania engine.

Additional improvements are on the way. In present day bus engines, the energy content of the fuel is utilized so that about 40% is converted into useful work, 25% is dissipated in the cooling water and the remaining 35% is discharged with the exhaust gases. So there is much energy to be saved, and some of our development work is oriented towards reducing the losses in the cooling water and the exhaust gases. One possible measure is the introduction of an additional exhaust gas turbine in series with the existing turbocharger. As illustrated in Figure 5, the power delivered by this additional turbine can be transmitted mechanically to the crankshaft across a gear train. This arrangement is known as a turbo-compound engine and will increase efficiency of the diesel engine towards 50%. The diesel engine should thus continue to be way ahead of any competitors as a prime mover for trucks and buses.

	EXHAUST EMISSIONS (13 Mode Cycle) g/BHPH			SMOKE EMISSIONS % USPHS		
	HC	NO_x+HC	CO	Acceleration	Lugging	Peak
USA FEDERAL REGULATIONS	1.5	10	25	20	15	50
SCANIA DS11(convent.bus)	0.7	8.3	1.5	13.2	7.7	31.2
SCANIA DS11(articul.bus)	1.2	9.3	1.5	16.8	4.8	36.6

If stricter limits are specified in the future for exhaust gas emissions, some modifications will have to be carried out on the engine.

The basic design of the Scania engine is however favorable for accommodating stricter emission demands. This fact, together with our ample resources for further development, will enable us to continue to offer exceptionally competitive engines, even if stricter emission regulations should come into force.

Development Forges Ahead

Few engines have as great development potential as the diesel engine -- towards increased output, reduced fuel consumption, lower noise level and lower emission values. At Scania, the development of diesel engines for trucks is on the leading edge of technology. This benefits us on the bus side, since we are assured that every improvement will have been thoroughly tested before it is introduced on our buses.

Intercooling is an example of such an improvement that may benefit bus engines. Intercooling results in a higher engine output, higher torque and lower specific fuel consumption. At the same time, it reduces the thermal stresses, and this contributes to increased useful life of the engine. Figure 4 shows the principle of intercooling on Scania engines.

Alternative Fuels

Scania bus engines are designed for running on diesel fuel. Every function and every component of the engine is designed to extract maximum energy from this particular fuel. At present day prices and availability of diesel fuel, no other fuel can therefore compete. But the world around us is constantly changing. Crisis situations sometimes arise to limit the availability of diesel fuel, national interests may affect the choice of fuel and extreme emission demands may also impose limitations. The opportunity for using alternative fuels in diesel engines exists. But major design modifications will then be necessary.

At Scania, we have carefully studied the characteristics of alternative fuels, how they affect the power output, what design modifications would be necessary, how materials are affected, etc. Extensive tests have been carried out at our engine laboratory on ethanol, methanol, vegetable oils, wood gas and liquified petroleum gas (LPG) for use in diesel engines.

Our main line of investigation into alcohol fuel concerned the use of alcohol in conjunction with an ignition improver, although we have also produced a dual-fuel system in which diesel fuel is used as ignition fuel.

In collaboration with certain special customers and a number of mass transit companies in Sweden and

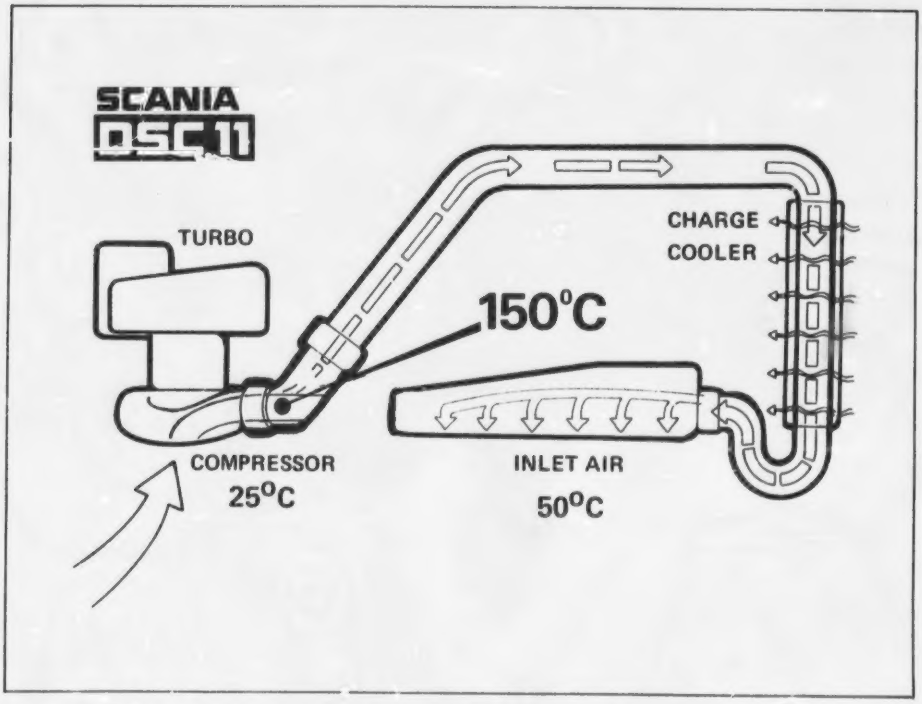

SCANIA
DSC 11
TURBO
CHARGE
COOLER
150°C
COMPRESSOR
25°C
INLET AIR
50°C

Figure 4 -- INTERCOOLING: Tests in Scania trucks have shown that intercooling improves performance while reducing thermal stress.

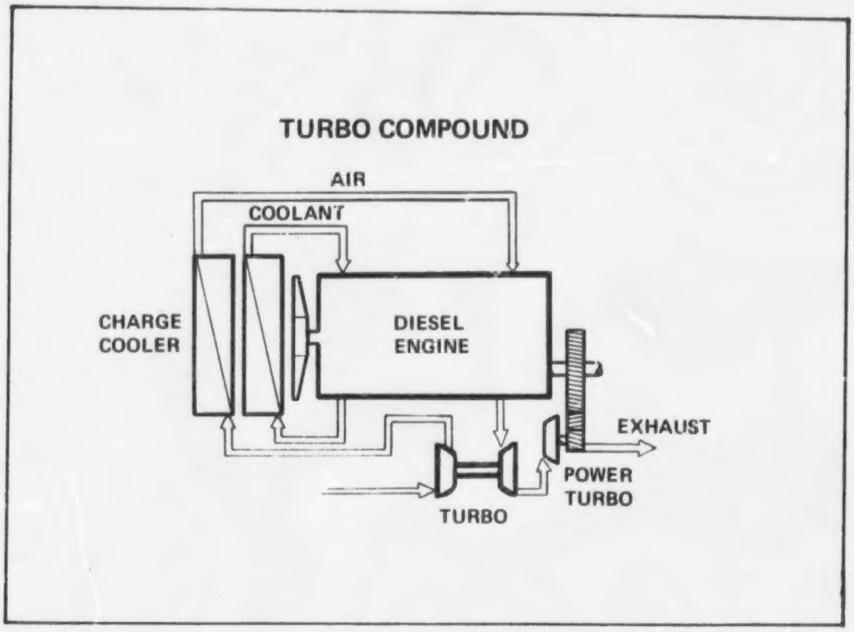

TURBO COMPOUND
AIR
COOLANT
CHARGE
COOLER
DIESEL
ENGINE
EXHAUST
POWER
TURBO
TURBO

Figure 5 -- TURBO COMPOUND: A second exhaust gas turbine in series with the turbocharger can deliver extra power to the crankshaft.

abroad, we have carried out successful tests on engines running on ethanol plus an ignition improver, on vegetable oils and on LPG.

LPG is being tested on its own as well as in combination with diesel fuel. For running purely on gas, we have equipped the engines with an electrical ignition system, carburetor and low compression pistons.

On mixed diesel fuel and gas operation, we inject 30% of gas, but this addition is gradually reduced to zero at idling speed.

Brazil is an example of a country in which national interests may place demands on alternative fuels being used. The country is completely dependent on imported fuel, but domestic raw materials are available for producing ethanol as well as vegetable oils. Extensive tests have been carried out on both of these alternatives.

We consider that diesel fuel is the most economical fuel at the present time. But we know that the situation may change and we are well equipped to adapt ourselves to any new conditions. We are fairly confident that we can carry out the necessary adjustments on our engines in a shorter space of time than that necessary for the fuel manufacturers to adjust their production to alternative fuels.

The Scania Bus is Equipped with a Four-Ratio Automatic Transmission for Comfort and More Reliable Operation

Gear shifting is a frequent task of the driver of a city bus. On average, he changes gears more than 300 times an hour, and this is hard work. Gear shifting in an automatic transmission takes place quickly and almost imperceptibly. This results in better comfort for the passengers and enables the driver to devote his undivided attention to the surrounding traffic. But the automatic transmission also offers better economy, particularly if it is the Scania GAV 762 transmission. Its ratios are selected so that shifting up will take place at the correct instant in city traffic, to ensure optimum economy. And the fact that gear shifting takes place appreciably more smoothly than on manual gear shifting is illustrated by Figures 6-A and 6-B.

The GAV 762 is actually a six-ratio transmission. Three of the ratios are mechanical and the three others are hydraulic. But we only use five ratios on our buses, and no more than four at a time: when accelerating, the two lower hydraulic ratios and the two higher mechanical ratios are used; when decelerating or retarding, the three mechanical ratios and the lowest hydraulic ratio are used. This provides optimum retarding effect.

The Scania GAV 762 automatic transmission incorporates a three-element torque converter with a stall torque ratio on stalling of no less than 6.0. We have therefore fitted a torque divider before the impeller of the converter, to distribute one-third of the input torque to the impeller and two-thirds of the torque directly to the central shaft. From the turbine, the stepped-up torque is transmitted through a sprag clutch to the same central shaft which will then have a maximum torque step-up of 2.7. The purpose of this arrangement is to achieve a simple and compact torque converter which, because the converter losses influence only during part of the power flow, has a high efficiency over a wide range of engine speeds.

By braking the sunwheel in the power divider by means of a disc brake, an overdrive of 0.66 is obtained on the central shaft. The following planetary Simpson-type gears give two ratios plus reverse and direct drive. A 60°-angle drive gearbox with a ratio of 20:13 provides an overall ratio of 1.015 in top gear and a maximum of 8.7 in bottom gear. These ratios may be altered in the future because of engine development.

A hydraulic retarder is provided immediately adjacent to the transmission. This will be a standard feature on our U.S. buses and is a good supplement to the engine exhaust brake. In addition, it naturally saves the wheel brakes. The retarder has three steps, which come into operation depending on how far down the brake pedal is depressed and from what road speed the bus is braked. This is designed to restrict the amount of heat generated and to give the passengers and the surrounding traffic a sense of the bus being braked under controlled conditions.

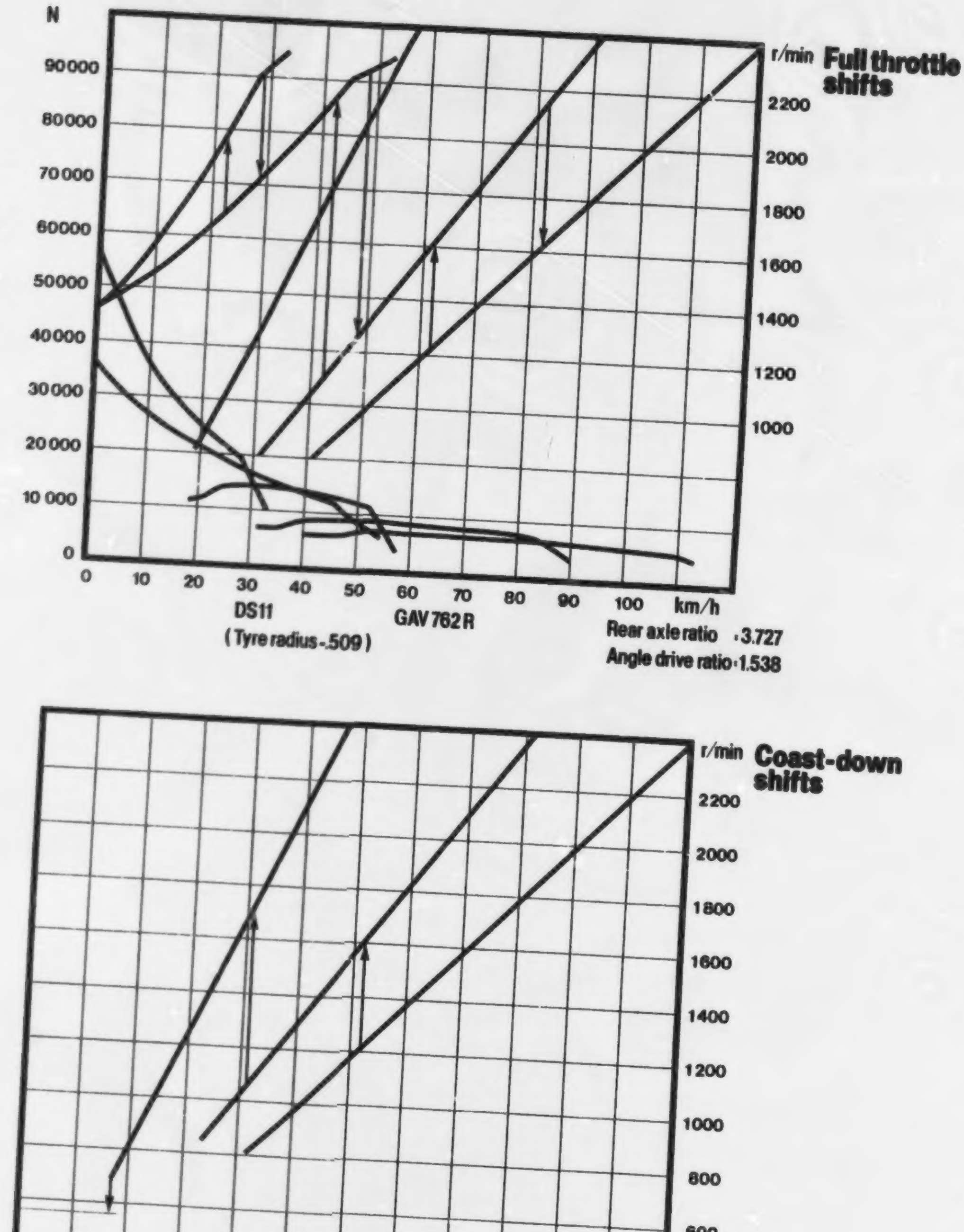
Continued Adaptation of the Automatic Transmission to Low-Speed Engines

As mentioned earlier, continued development work is pursued on the bus engine, and the automatic transmission must be adapted in parallel with engine development. Figure 7 shows a curve of the torque absorbed by the hydraulic section at different engine speeds. The point at which the curve intersects the engine torque curve is known as the stall point. This determines the engine speed with the bus stationary and the engine running at full throttle. It is known from experience that this speed should be close to the speed at which the engine develops maximum torque. The transmission must therefore be adaptable to different engines. We are now preparing different ratios in the torque divider in order to maintain the torque level supplied to the torque converter. Also by differing the blade angles of the impeller, the torque converter can be adapted to give the correct stall speed. Thus, we can select a speed range that will ensure the best efficiency for a particular engine. Adaptations of this type offer the optimum economy and power for combinations of engine and transmission.

Rear Axle Gear with Reduction

As mentioned earlier, our automatic transmission itself provides an overdrive. This is converted to direct drive by the angle drive gearset, which itself is necessary since the engine is mounted transversely. It has thus been possible to reduce the reduction ratio in the rear axle. This has a beneficial effect on the sound emitted by the rear axle.

The gear teeth of the rear axle generate sound that may be amplified by resonance frequencies in the bus. The resulting sound level may be uncomfortably high. We are therefore testing varying numbers of teeth and various tooth forms in the complete bus.



Figures 6-A and 6-B -- SCANIA AUTOMATIC: The Scania GAV 762 is a fully-automatic, 4-speed transmission.

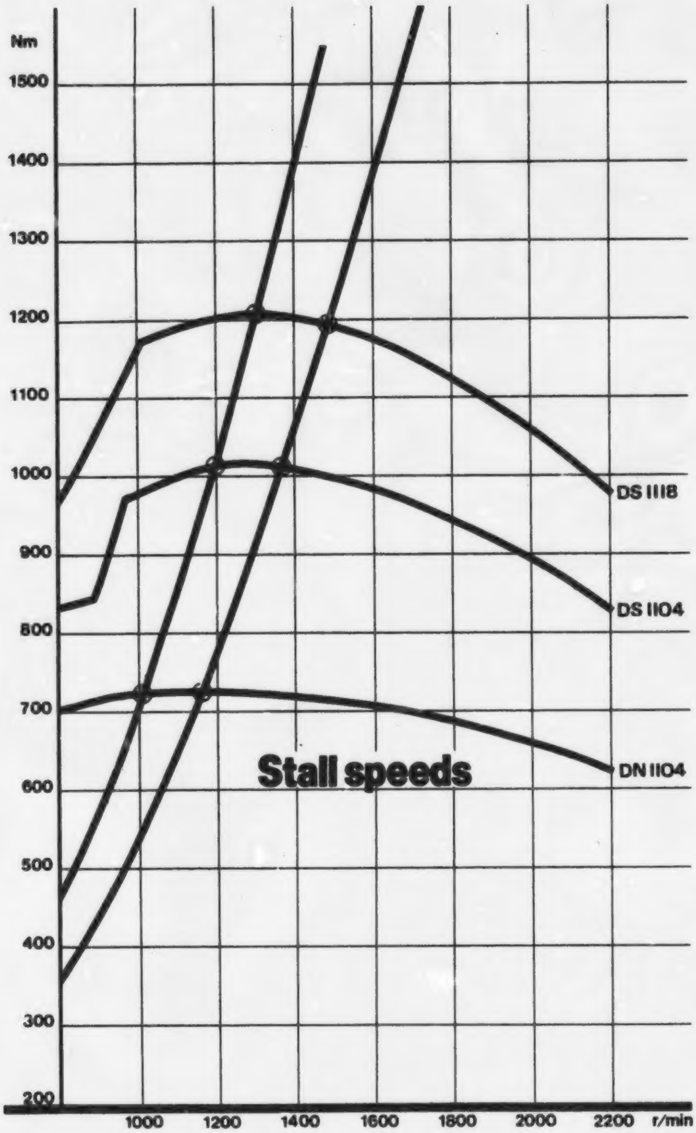


Figure 7 — STALL SPEED: For best performance, the stall point should be as close as possible to the speed at which the engine develops maximum torque. It is therefore important to carefully match engine and transmission.

Integrated Development, Design and Production of the Power Transmission Line Ensure Optimum Economy

Scania is responsible for the development, design and testing of all units in the power transmission line. We also carry out the production work. As a result, we provide every part of the power transmission line. When fitted to our complete bus chassis, they will jointly ensure optimum economy, a low sound level and low exhaust emissions.

This overall integration gives us full control of the development. Whenever an individual part is modified, the consequences this may have on other functions are always taken into account. The dependent parts are then adapted to ensure continued balance of the complete unit.

Economy in Every Part

We have so far discussed economy in some detail, although mainly in terms of low energy costs. But economy involves appreciably more. A bus that performs reliably and with little downtime also represents economy. At Scania, we leave nothing to chance in this respect. The type of advanced transportation equipment we produce does not allow us to leave anything to chance.

Extensive tests are undertaken whenever an entirely new bus is being developed or whenever new components are introduced. The tests start indoors, and technically advanced aids are used. The tests are then continued on test tracks under conditions that are much more difficult than those to which a bus is normally subjected. This is followed by tests in normal service, with careful follow-up at the customers' plants, and field tests on a larger number of units before series production is started. These practical tests on materials and performance provide reliable indications on how the planned improvements will perform in practice, and we can determine right from the start the service frequency that may be expected. This provides us a guarantee that a new feature will actually perform as intended and even under more difficult conditions than in normal traffic.

We have well-specified quality demands in our production system. Every component of a diesel engine, for instance, is subjected to several inspections, and running-in is carried out after final assembly. Running-in comprises two hours of operation under different load conditions. Readings of pressures, temperatures, fuel consumption, smoke, torque and output are then recorded. If deviations from the normal values for the engine are detected, the engine is examined and the cause of the deviations receive attention. The automatic transmission is subjected to correspondingly strict inspection of the components and the complete unit. Very stringent demands on cleanliness and precision are made before and during final assembly.

All Conceivable Traffic Situations are Simulated by Computer

Scania has long been using computerized simulation of all conceivable traffic situations and road conditions, Figure 8-A. This method, known as the Scania Transport Simulation System (STRASS), is appreciably faster than practical road tests and provides more reliable information on the various transmission line design factors that may have a bearing on the economy.

In brief, the method involves feeding in the necessary data for the bus onto magnetic tape. This data may include particulars of the engine power, fuel consumption as a function of the engine speed at different loads, the ratios in the transmission and rear axle, engine speeds on gear shifting, speed limits, rolling resistance, etc. The appropriate traffic situation is fed in onto another tape. This may contain particulars of the number of starts and stops, traffic lights, traffic intensity and topography. Figure 8-B shows an example of how the computer records various values during a journey.

In parallel with the computerized simulation, we also undertake practical road tests. However, these usually merely demonstrate that the computer provides appreciably more reliable information on how the bus behaves in varying traffic situations.

Follow-up is Vital to Optimum Economy

Throughout its useful life, the bus must serve as a reliable and comfortable means of transporting passengers -- a task for which it has been designed and tested. So we do our best never to lose touch with the buses we have delivered. And if a bus is to be introduced on a new market, the introduction is preceded by thorough investigations into the reactions of drivers as well as passengers. A typical example is the scheduled introduction on the U.S. market. For a period of time, Scania buses have been in regular traffic in the U.S. This has enabled us to carry out comparative performance tests, check the fuel consumption, adapt the interior to suit local conditions, and follow up and adjust the service requirements.

Service is important. Way back at the design stage, we ensure that every part is designed for the simplest possible servicing. And our replacement system is well developed, which has practically eliminated time-consuming repair work. Service is instead confided to simple and fast replacement of factory-reconditioned components. Downtime is thus minimized and the active operating time is therefore increased. This is obviously beneficial to the overall operating economy.

The Driving Technique Affects the Economy of the Bus

In spite of all measures adopted to improve the economy of the bus, the driver still has a decisive influence on the economy -- in the form of fuel consumption and useful life -- and also on the noise and exhaust emissions. Automatic transmissions, retarders, etc., will be to no avail if the driver is heavy-footed on the accelerator and brake pedals. This will quickly wipe out the effect of all the good characteristics incorporated into the bus by years of development. With this knowledge in mind, we have devoted determined effort to effective driver training. This is based on the driver instruction

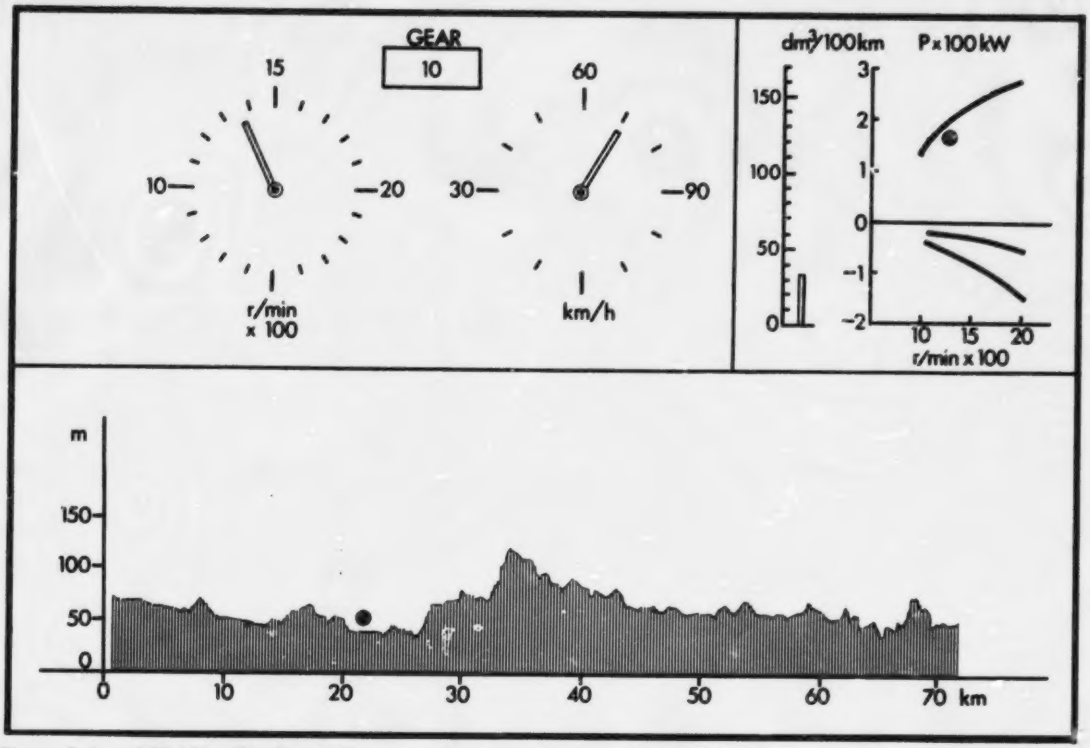


Figure 8-A — STRASS: The Scania Transport Simulation System (STRASS) is the most reliable test for evaluating drivetrain designs.

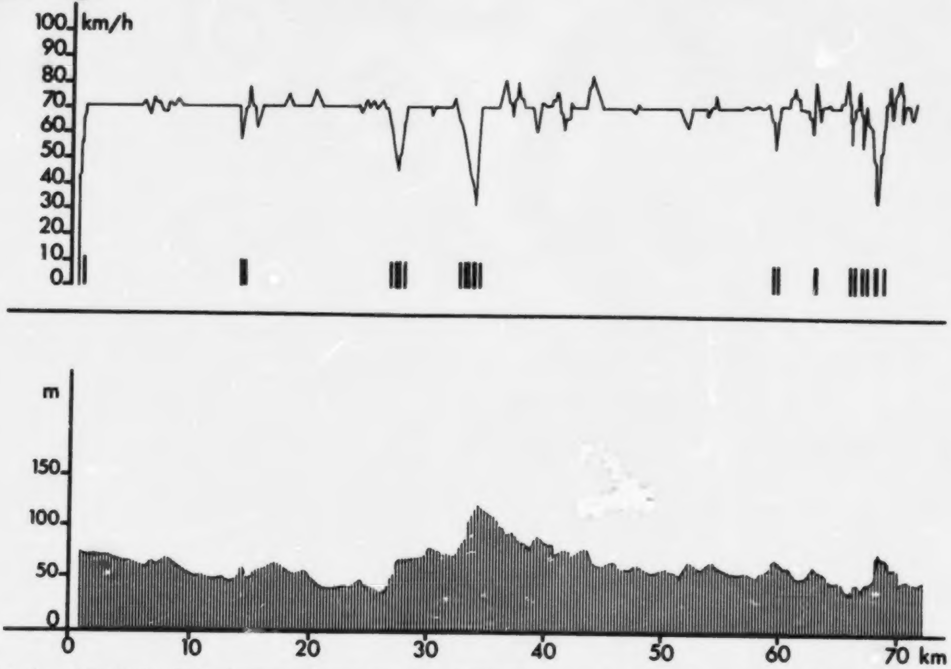


Figure 8-B — STRASS: This diagram shows how the STRASS computer records various values during a simulated trip.

manual entitled "Driving the CN112". This contains general rules for how the bus should be handled to provide the best possible satisfaction to the driver as well as the passengers. But we are not content with this alone. The driver must also practice and must be given insight into how the bus should be handled in a particular traffic situation to ensure that the optimum condition of the bus will be maintained.

It is obviously unsatisfactory that the human factor should be able to affect the economy of the bus to such a large extent. As a result, we have introduced an electrically controlled accelerator mechanism on our U.S. buses. This basically means that the mechanical linkage has been replaced by an electric cable. The mechanical linkage was particularly difficult to incorporate into articulated buses, and this is therefore the type of bus to which the electrical system was first applied. In simple terms, the system consists of an accelerator pedal actuated potentiometer that controls the injection pump. If connected to a microprocessor, this system can provide numerous other advantages. As an example, the acceleration can be controlled or a constant speed control can be introduced. The facilities offered by the electronic control system are practically unlimited.

It may be mentioned in this context that electronics are well on the way to taking over some of the control functions in the more advanced manual transmissions.

Electronics can be connected to these transmissions to record quickly any changes in the traffic situation and automatically indicate the most appropriate ratio to suit the prevailing conditions. But the driver always has the opportunity to override the computer and select the ratio he considers best. We have called this equipment Computer Aided Gear shifting or CAG for short, and we are internationally very well ahead in this area (Figure 9).

In summary, much has happened in the development of the power transmission of a bus as regards optimization of the fuel consumption, sound level and exhaust gas emissions. But, as mentioned earlier, developments are still forging ahead. Much remains to be done and many interesting new features can undoubtedly be expected from Scania in the future.

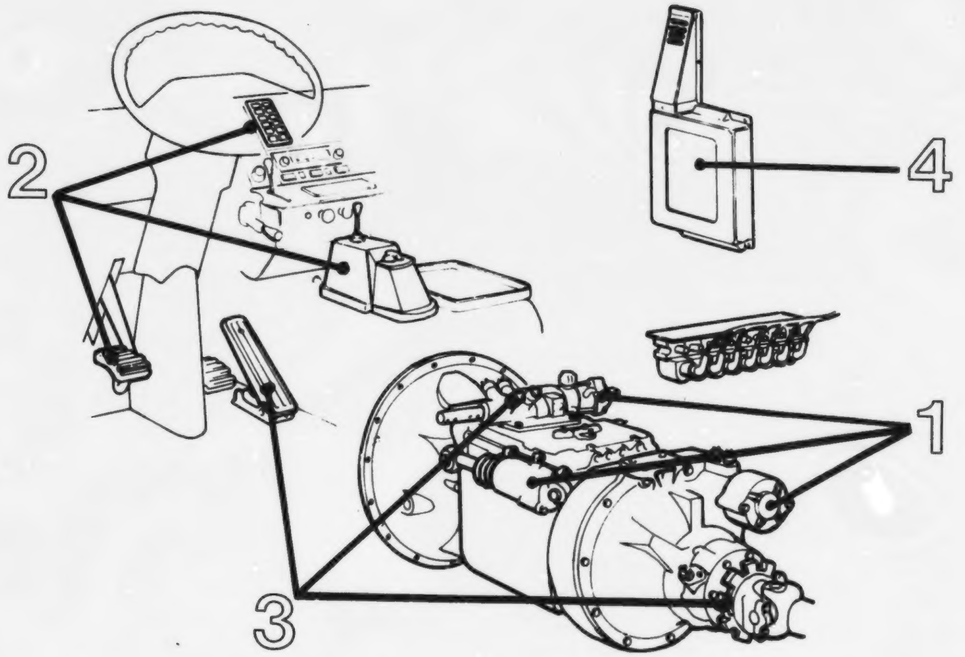


Figure 9 -- INTELLIGENT GEARBOX: Scania's computer-aided gear changing system works like this: (1) Actuating cylinders change gears; (2) the driver communicates with the system through gear shift indicator, gear lever, and mode selector switch and clutch pedal with buzzer that tells driver when the gears are being changed; (3) vehicle status monitoring units: throttle position, gear engaged, and road speed; (4) the microprocessor assesses vehicle status parameters and recommends the optimum gear ratio.

USE OF THE M.A.N. METHANOL-FUELED ENGINE ON CITY BUSES: FUNCTIONAL PRINCIPLES AND EVALUATION IN ACTUAL SERVICE

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Summary

Given world's limited petroleum reserves, it is essential that this primary source of energy for transportation needs be replaced by other sources of energy. For this reason alternative fuels based on alcohol are rapidly gaining importance. One obvious measure would be to utilize alcohol in the most efficient way possible, namely to fuel a diesel engine. Here the difficulty is that this fuel does not auto-ignite easily.

The M.A.N. "FM" combustion process, which was derived from a direct injection diesel engine, together with the use of spark plugs to assure reliable ignition, offers an effective solution to this problem. The basic operating principles of this alcohol engine are: a compression ratio equivalent to that of a diesel engine, direct injection, the formation of a fuel film in the combustion chamber, and a more or less conventional ignition system.

The development of the M.A.N. underfloor engine for methanol-fueled buses was continued with in-vehicle functional testing. The ignition system was simplified and made less expensive by switching to the use of a spark plug whose design was close to that of a plug already in mass production. The efficiency achieved with this spark plug is comparable to a large extent to that of the direct injected basic diesel engine. The California standards for exhaust gas emissions were met. Mechanical wear in the engine so far has not been observed to be higher than that for the diesel engine. The extended service behavior of the lubricating oil is good.

1. Introduction

Various concepts utilizing alternative energy sources for transportation needs are becoming increasingly important throughout the world. Alcohols such as ethanol or methanol, which can be obtained either through agricultural production or from raw materials like coal and natural gas which are still available in large quantities, clearly play a key role in these concepts. Countries whose climatic conditions are especially favorable to the cultivation of commercial crops containing sugar or starch have a good potential for at least partially meeting the energy needs of the transporation sector with biologically produced alcohol, in other words: ethanol. In regions which are climatically less favorable, but which have relatively large deposits of coal or natural gas, methanol is the most promising alternative to current petroleum-based fuels.

If a new fuel such as methanol is to be brought into the market and widely used for transportation needs, suitable vehicles as well as an acceptable distribution system are necessary. Whether an available distribution line previously used for a petroleum-based fuel can be used, or whether an additional tank system will have to be integrated into the present network of filling stations, will have to depend on the actual conditions and needs of the various countries and regions. At any rate, investments will be needed and a relatively long introduction period can be expected. For this reason, one would anticipate that the new fuel can be introduced more easily on isolated fleets of vehicles, since the costs for the centralized fuel supply would be lower in this case. In addition, suitable vehicles can be developed, purchased, and serviced more easily with an isolated fleet, and critical know-how can be gathered more easily than would be the case if such vehicles were dispersed widely throughout the market from the beginning on.

In the commercial vehicle sector the typical representatives of such fleets are municipal or regional public transit authorities. Thus, M.A.N. decided to concentrate its activities relating to the use of alcohol fuels mainly on city buses. The results obtained from this development program, however, can also be applied to other vehicle and engine types.

2. Considerations Regarding The Engine Design Concept

Aside from the primary goal of making highway transportation less dependent on petroleum as a source of fuel, when methanol is used as the alternative, one must also try to achieve the ongoing goal of obtaining the best possible energy conversion efficiency in the vehicle.

To date, the diesel engine remains the thermal-energy-driven machine which has the best thermal efficiency. For this reason, it is only natural to attempt to find a way to use methanol with this engine concept. The most promising approach appears to be the use of the alcohol fuel in its pure form. When methanol is mixed with conventional diesel fuel, for example, the problem of poor miscibility is encountered, which could be solved by blending in additives to act as intermediaries to aid dissolving. Current information, however, indicates that this method would result in significant increases in the price of the fuel.

If methanol were blended in with the previously used fuel in ever-increasing proportions during the introduction period, the engine design would also have to be adapted to these blends, since the fuel characteristics would be continually changing due to the relative differences in the characteristics of the blend components. Alongside this conceivable strategy for introducing the alternative fuel on the market, it seems at least equally reasonable to provide the final form - namely pure methanol - immediately and to increase the number of methanol-fueled vehicles to meet the amount of methanol available.

The most important properties of diesel fuel, methanol, and ethanol are summarized in Figure 1. A comparison of the values for ethanol and methanol shows that - on the whole - ethanol has better potential for use in combustion engines. Therefore, the development of a combustion process for methanol will unavoidably mean that ethanol can be used as well.

The calorific value of methanol is only slightly less than half that of diesel fuel and the heat of vaporization relative to weight is more than four times greater for methanol, while being nearly ten times greater relative to calorific value. Thus, the energy required to generate the air/fuel mixture is extremely high. Methanol's cetane rating of 5 means that this fuel auto-ignites with extreme difficulty.

Thus, the primary requirement of a methanol engine is that it must be able to generate sufficient energy to form the air-fuel mixture. Furthermore, it must be able to ignite the fuel reliably in spite of the fuel's resistance to auto-ignition. Finally, a methanol engine must operate at the highest possible compression ratio in order to keep fuel consumption low.

With a spark ignition engine, provisions must be made above all, for cold start and warm-up, since a stoichio-metric methanol/air mixture is cooled 122°C during vaporization. With gasoline, on the other hand, this temperature drop is only about 22°C. This means that expensive preheating equipment and heat exchangers are unavoidable. With the current state of technology, a low boiling point additive is mixed with methanol to make its vaporization characteristics approach those of gasoline. By using spark plugs, ignition itself is not a problem. Given the relatively high octane rating of methanol, the compression ratio of the spark-ignited engine can be increased to approximately 12.5:1 [twelve point five to one], but is still significantly lower than that of a diesel engine. The throttle controls in the partial load range also result in a further reduction in efficiency.

The conventional commercial vehicle diesel engine has a high compression ratio and does not use throttle controls - both facts favoring improved fuel consumption - and has the further advantage of utilizing direct injection. With this engine the heat of vaporization can easily be supplied by the compressed air at the end of the compression stroke. Of course, pure methanol could only be made to auto-ignite with an excessively high compression ratio. A solution to this problem would be the possible use of a fuel additive to accelerate ignition, which would raise the cetane rating to a value approaching that of diesel fuel. The disadvantage of this solution would arise from the additional cost penalty for the fuel additive.

Another possibility is the ignition stream method. Here a relatively small amount of diesel fuel is injected into the combustion chamber, where it burns and ignites the alcohol. This fuel, here methanol, can be prepared for combustion by means of external air/fuel mixing using a carburetor or intake manifold injection, or internally, using direct injection. In both instances two different fuels must be carried on the vehicle and supplied separately to the engine through two systems.

3. The M.A.N. "FM" Alcohol-Fueled Engine

One advantageous way of using methanol to power automotive vehicles is offered by a combustion process derived from a direct-injected diesel engine which, however, uses a spark plug to ignite the mixture. This combustion process was originally developed by M.A.N. to further improve the multiple fuel burning capability of the M.A.N. "M" diesel engine for the use of high octane gasoline (1). This process is referred to as the "FM" process.

In order to reduce the roughness typically encounted with direct injection engines, the M.A.N. "M" diesel engine - which served as the starting point for the development of the "FM" multi-fuel engine - uses a method of controlling formation of the mixture and the combustion process which has not been used elsewhere in this form. This closed-loop control mechanism is based on the functional separation of injection and mixture formation. To accomplish this, most of the fuel injected into the cylinder collects on the wall of a spherical combustion chamber sunk into the piston head. The fuel vaporizing off the resulting film-like coating is then gradually carried to the combustion site by the air circulating in the combustion chamber. The necessary heat of vaporization is primarily generated from the flame radiation. Therefore, the speed of mixture formation depends on the existence and intensity of the combustion itself. The system prevents quantities of ignitable mixture in excess of that needed for ignition from being generated prior to combustion. This leads to a reduction in the rate of pressure increase and, hence, to a lowering of the associated combustion noise.

When running the engine on fuels such as gasoline, methanol, or ethanol, which do not auto-ignite easily, the air/fuel mixture is formed according to the same principle as with diesel fuel. In order to achieve reliable auto-ignition, the compression ratio would, of course, have to be increased to values of 25:1 [twenty-five to one] or more. However, such high compression ratios also generate high mechanical loads in the engine. The obvious answer then is to use an outside source of ignition so that firing begins at the correct time for compression ratios between 16:1 and 18:1 - values which are suitable for operating M.A.N. "M" engines. The subsequent generation of the air/fuel mixture and the progress of combustion also remain the same in this case.

In spite of a compression ratio which is unusually high for a spark ignition engine, the combustion is free of knock-related processes. This is due to the clearly defined spatial configuration of the stratified charge in the piston combustion chamber, which prevents the appearance of mixture components tending to auto-ignition in zones which are outside the combustion chamber and distant from the flame. A combustable mixture only develops at the fuel film in close proximity to the source of ignition and later the flame.

Figure 2 shows the principal components of the "FM" combustion chamber. The injection nozzle and the stream of fuel can be seen in the foreground. This stream of fuel has already spread out in the spherical recessed combustion chamber to form a film. The spark plug, located opposite the injection nozzle, projects down into this area. The cross-sectional areas of the injection orifice and the injection pump piston have been dimensioned to match the necessary injection charge, which is determined based on the calorific value of the respective fuel.

Thus, the principal characteristics of the "FM" engine design are:

- a diesel engine compression ratio
- direct injection using single-hole nozzles
- formation of a fuel film on the combustion chamber wall
- an electric ignition system.

The high compression ratio of the "FM" engine naturally means that its fuel economy is just as favorable as that of a diesel engine.

The direct injection and electrical ignition system make the "FM" engine particularly suitable for methanol operation. In contrast to engines on which the air/fuel mixture is formed outside the combustion chamber by means of carburetors or manifold injection systems, on the "FM" engine cold starting and warm-up do not present any particular difficulties. With direct injection, the high heat of vaporization for methanol does not need to be obtained from intake air at ambient temperatures. Instead, with a cold engine this heat can be obtained from the compressed charge of air in the cylinder at final compression temperature - in other words between approximately 500 and 600°C. This fact, together with the presence of an electrical ignition system, means that starting performance is independent of wide ranges in ambient air temperature.

With the engine warmed up to operating temperature, the direct injection system has the further advantage that a portion of the heat of vaporization can be taken from the engine components, for example, the walls of the combustion chamber and the spark plug electrodes. On the one hand, this lowers thermal stress on these components, and on the other hand, the energy used to heat the combustion chamber walls is cycled back into the process.

4. The Development of the Process and the Necessary Components.

The initial tests with methanol were performed in 1974 on a nonproduction 4-cylinder engine with a 92-mm bore and a 100-mm stroke. Later, a 6-cylinder engine was used with 108-mm bore and 128-mm stroke. In mid-1979 this engine was installed on a tourist bus for vehicle testing. A number of reports have already been published on the results of these tests (2,3).

The M.A.N. system was further developed using an 11.4-liter 6-cylinder model D 2566 FMUH engine (Fig. 3), which is suitable for underfloor installation in buses and was derived from the corresponding standard production diesel engine (4).

The spark plug which was previously used in this engine and whose design was based on a system developed for multiple-fuel operation, did not meet the necessary requirements for large scale production (Fig. 4). The two electrodes, which extended well beyond the cylinder head plane, had to be installed at a definite angular orientation relative to the combustion chamber in order to supply the best possible mixture across the spark gap. For this reason, the spark plug had to be bayonet-mounted with a locking system to prevent rotation. This required a relatively elaborate spark plug mounting system, consisting of several individual parts.

This led to the need to develop a simpler and less expensive spark plug - most logically based on a current large-scale production part. This meant that a screw-in-type spark plug with a standard thread would be needed in place of the bayonet-mounted plug (Fig. 5). In order to make such a design independent of a particular spark gap position, three ground electrodes were arranged in a star shape around the center electrode. This makes it possible for a plug which has been screwed into the engine without seating at a particular angular orientation to operate perfectly through the entire speed and load range (5).

The development was also combined with a change in the shape of the combustion chamber, so that electrode length could be reduced from 25mm to 15mm. This significantly lowered the thermal stress on the electrode and, thus the rate of electrode erosion.

The construction of this spark plug is very close to that of a model which is manufactured in high volume. The only difference lies in the length and shape of the electrode. Hence, specification and cost reductions can also be obtained at the ignition wiring connections and at the plug mounting system. Changing spark plugs is now identical to the conventional operation on SI engines.

An engine of the design shown in Figure 5 was used to generate a fuel consumption map as shown in Figure 6 to document the current status of developmental work. Aside from slight losses in efficiency in the upper load range, practically no differences could be noted in comparison with the earlier results using the 2-electrode plug. On the whole, efficiency is equivalent to that of the base diesel engine.

Figure 7 shows the full-load performance curves for this methanol engine in comparison with the conventional diesel engine. The fact that the exhaust gas is free of particulates permits the torque curve to increase across the full speed range, so that a significantly higher torque is available in comparison with the diesel engine. This is especially true at the lower engine speeds.

Cold starting is achieved without difficulty down to -20°C. The engine fires after a few revolutions and can be accelerated immediately. The lower temperature limit at which starting is possible was not determined.

Figure 8 shows the results from the 13-mode exhaust gas test. These results were obtained using an exhaust gas catalytic converter, whose service life with the methanol was not limited by the accumulation of particulates, sulphur, or lead. The measurements of hydrocarbon emissions were made taking into account the fact that measurements with an FID only record approximately two-thirds of the methanol, since it contains oxygen. In order to determine actual emissions, the observed value was increased accordingly.

Aside from modifying this "FM" engine for methanol, tests were performed with ethanol. These tests confirm that the engine operates on ethanol just as well as methanol.

5. Actual In-Vehicle Service

In order to collect data and gain experience with actual vehicle operation in addition to developing the engine on the dynamometer, engines from the first stage of development - this is, with 2-electrode spark plugs - were used in service on urban transit routes. In mid-July 1981 a model SL 200 methanol-powered coach was used for service in Berlin by the BVG (Berlin Transit Authority) (Fig. 9). At the end of October 1981 a second SL 200 city bus was turned over to the ARA (Auckland Regional Authority), Auckland, New Zealand (Fig. 10).

By September 1982 the Berlin bus had accumulated 73,000 km. By this time the Auckland had covered approximately 30,000 km. In both cases drivers evaluated the bus driveability positively.

The engines start immediately - both cold and at operating temperature. One of the methods used to insure this was to supply the fuel to the injection pump suction chamber by means of an additional fuel delivery pump during cranking. In this way the possibility of vapor lock could be eliminated (Fig. 11). During engine operation the electric fuel pump also supports the mechanical fuel pump.

Figure 12 shows the route fuel consumption for the Berlin coach in comparison with the other diesel buses used there. Because of the low calorific value of methanol, volumetric fuel consumption is more than twice that encountered with the diesel engine. In order to obtain a meaningful comparison, the methanol consumption was converted to an equivalent amount of diesel fuel. The bars on the left - identified by number 1 - designate the originally installed engine from the first stage of development. The fact that the energy consumed by the methanol bus is approximately 13% higher is attributable to the methanol engine's approximately 20% higher torque in the low speed range in comparison with the diesel engine. Naturally, the drivers made use of this torque for faster acceleration. In stop-and-go inner city traffic, this has the effect of increasing fuel consumption.

After 47,000 km was covered in service, this engine was replaced with one representing the second stage of development. On this bus the torque was reduced to the value offered by the standard diesel engine. This meant that the methanol bus had the same acceleration characteristics as the diesel bus.

As the right-hand bars (identified by the number 2) show, the same phenomenon is also reflected in the energy consumed by the methanol bus. The same fuel economy figures were obtained for the Auckland bus, which was also equipped with an engine from the first stage of development. It must be noted that the Berlin bus was run on M 100 methanol fuel, which contains 5 to 7% isopentane. The Auckland bus was run on pure methanol. As a consequence, the energy consumed during service in Auckland is lower and is equivalent to 45 liters per 100 km diesel fuel [5.2 mpg].

A multi-grade SAE 15 W/40 developed especially for methanol engines is used for lubrication. The quality of the lubricating oil is monitored on an ongoing basis jointly with the supplier. The oil change interval was first set at 10,000 km. Results to date indicate that the specified change interval is corroborated by the extended service performance of the oil; indeed, this performance suggests that the interval can be extended. Engine wear, as indicated by abraded metal in the oil, is no higher than with a diesel engine.

When the engine installed in the Berlin bus was disassembled after 47,000 km of operation, results of dimensional inspection of all major engine parts, such as cylinders, pistons, piston rings, valves, bearings, etc. corresponded to similar measurements for a diesel engine operated for a similar period.

The injection nozzles were first inspected after 20,000 km had accumulated. It was found that the only significant traces of wear could be detected in the pintle seating area. Such traces of wear were in fact larger than those for diesel opeartion; the result being a 0.02-mm increase in stroke. The observed wear mainly caused the pintle seat to be wider toward the tip. This caused the pressure required to open the injection nozzle to drop from 175 bar to approximately 150 bar, but since the spring force had remained nearly constant, the hydraulic characteristics of the injection nozzle were not changed. For this same reason, the operating behavior of the engine was not affected. The remaining injection nozzle components did not exhibit any significant wear. The engine service accumulated to date is not yet sufficient, however, to permit conclusions to be drawn as to the anticipated service life of the nozzle during methanol operation. Additional developmental work has been undertaken in the meantime to extend the service life of the nozzle through the use of different materials and processes.

In comparison with diesel operation, the injection pump used here did not exhibit any particular wear-related problems. Experience so far indicates that it will probably even be possible to discontinue supplying sealing oil to the pump elements, in order to return to a simple diesel injection pump concept.

Methanol-resistant materials recommended by the various manufacturers were used on the entire engine and bus fuel system. This was true for the fuel filter cartridges as well as for hoses and other synthetic parts. Nevertheless, fuel supply problems were encountered after 15,000 km bus operation. The electrically driven fuel supply pump blocked up due to deposits which caused the pump armature to stick. The origin of these adhesive substances has since been determined. On the one hand, high molecular weight substances seem to be released at first from the surface of the methanol - resistant parts in the fuel system. Experience has shown that this process stops after awhile.

On the other hand, components of the lubricating oil used in the injection pump, such as additives to improve flow, find their way into the fuel system. This is probably due to the fact that sealing oil is supplied to the pump elements. For this reason it would be desirable to get by without the sealing oil circuit.

The erosion characteristics of the 2-electrode spark plugs with extremely high-quality electrode material which were used in vehicle operation resulted in service intervals of approximately 25,000 km. Comparative studies were made on test stands. These studies showed that the inexpensive spark plug designs referred to above can attain service intervals over 12,000 km. Given the progress made on this project to date, the spark plugs would have to be renewed and the oil changed at a 10,000-km service interval. However, old spark plugs could be reused several times after being regapped, since the lack of combustion deposits in the methanol engine means that no deposits build up on the spark plug insulators.

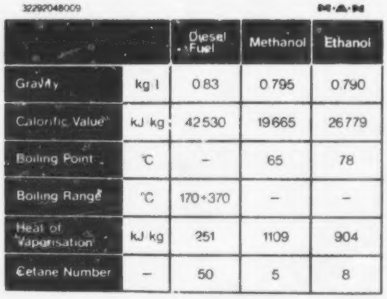
So far no problems have occurred with the remaining components of the ignition system, such as the distributor and induction-type pulse generator, the ignition coil, and the control units.

References

1. F. G. Chmela, "High Compression Stratified Charge Engines and Their Suitability for Conventional and Alternative Fuels." Conference on Stratified Charge Automotive Engines, London, Nov. 1980, Paper C400/80.
2. "Neuen Kraftstoffen auf der Spur" [On the Trail of New Fuels], Bundesministerium für Forschung and Technologie, Bonn, 1974.
3. A. Neitz and F. Chmela, "M.A.N. FM Process to Enable Diesel Engines to Burn Methanol." First International Automotive Fuel Economy Research Conference, Arlington, Virginia, USA, Oct. 31 - Nov. 2, 1979.
4. A. Neitz and F. Chmela, "Results of MAN FM Diesel Engines Operating on Straight Alcohol Fuels." IV International Symposium of Alcohol Fuels Technology, Guaruja-SP, Brazil, Oct. 5 - Oct. 8, 1980.
5. A. Nietz and F. Chmela, "The M.A.N. Methanol Engine Powering City Buses." Fifth International Alcohol Fuel Technology Symposium, Auckland, New Zealand, May 13-18, 1982, Paper C2-23.

List of Figures

1. Properties of diesel fuel, methanol, and ethanol.
2. Combustion chamber of FM engine.



32292048009

		Diesel Fuel	Methanol	Ethanol
Gravity	kg l	0.83	0.795	0.790
Calorific Value	kJ kg	42530	19665	26779
Boiling Point	°C	–	65	78
Boiling Range	°C	170÷370	–	–
Heat of Vaporisation	kJ kg	251	1109	904
Cetane Number	–	50	5	8

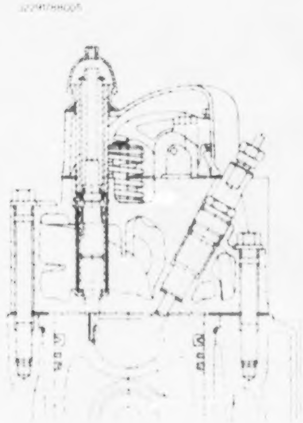
Eigenschaften von Dieselkraftstoff, Methanol und Äthanol
Properties of Diesel Fuel, Methanol and Ethanol

Figure 1

M A N
Kraftstoffstrahl

Figure 2

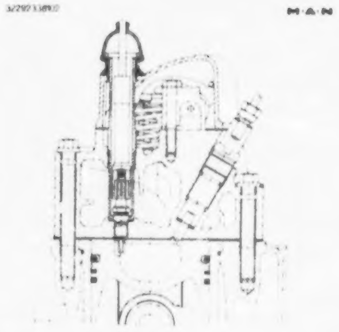
Figure 3



MAN Motor
D 2566 FM

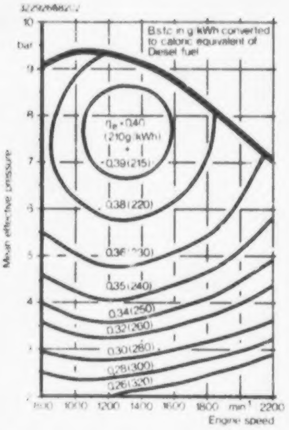
MAN Engine
D 2566 FM

Figure 4



MAN Motor D2566 FM
MAN Engine D2566 FM

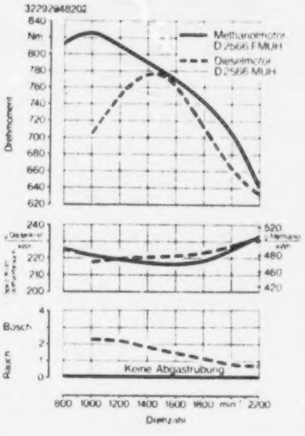
Figure 5



Effektiver Wirkungsgrad des Methanolmotors D 2566 FMUH

Brake Thermal Efficiency of Methanol Engine D 2566 FMUH

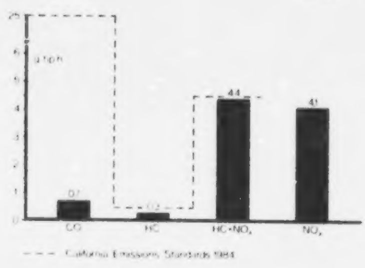
Figure 6



Vollastkennlinien des Methanolmotors D 2566 FMUH und des Dieselmotors D2566 FMUH

Full load characteristics of Methanol engine D2566 FMUH compared with Diesel engine D2566 FMUH

Figure 7

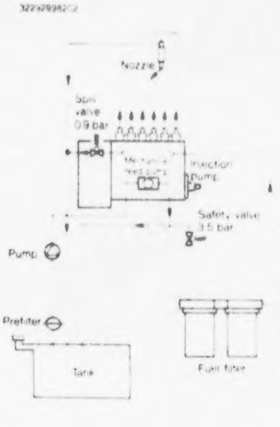


13 Mode Cycle Results of Methanol Engine D 2566 FMUH

Figure 8

Figure 9

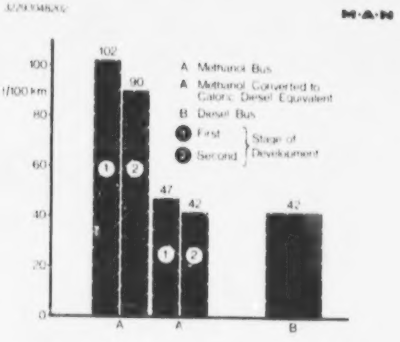
Figure 10


32292998202
Nozzle
Spill valve 0.9 bar
Methanol feed pump
Injection pump
Safety valve 3.5 bar
Pump
Prefilter
Tank
Fuel filter

Kraftstoffsystem des MAN-Standardlinienbusses mit Methanolmotor D 2566 FMUH

Fuel Supply System of MAN-City Bus with Methanol-engine D 2566 FMUH

Figure 11



Kraftstoffverbrauch eines Standardlinienbusses mit Methanolmotor D2566 FMUH

Fuel Consumption of M A N City Bus with Methanol Engine D2566 FMUH

Figure 12

3. M.A.N. bus engine D 2566 FMUH for alcohol fuels.
4. M.A.N. D 2566 FM engine with previous spark plug design.
5. M.A.N. D 2566 FM engine with new spark plug design.
6. Brake thermal efficiency of the D 2566 FMUH methanol-fueled engine.
7. Full-load characteristics of the D 2566 FMUH methanol engine and the D 2566 FMUH diesel engine.
8. 13-mode cycle results for the D 2566 FMUH methanol engine.
9. M.A.N. city bus with the D 2566 FMUH methanol engine.
10. M.A.N. city bus with diesel, LPG, and methanol engines.
11. Fuel system for the M.A.N. city bus with the D 2566 FMUH methanol engine.
12. Fuel consumption of M.A.N. city bus with the D 2566 FMUH methanol engine.

CONTINUOUSLY VARIABLE TRANSMISSIONS FOR URBAN BUSES — A STATUS REPORT OF EUROPEAN RESEARCH AND DEVELOPMENT

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USA

1.0 INTRODUCTION

The function of a transmission is to match the characteristics of a power unit (i.e., a diesel motor) to those of a driven unit (i.e., vehicle). Traditionally, this function is performed gear boxes in association with a clutch (manual) or a converter (automatic). Since the gear box allows only stepwise changes, the converter or the clutch is necessary to smooth out the effect of these discrete changes. This smoothing process, not always easy to control, is at the origin of the longitudinal jerk experienced during gear changes.

In a continuously variable transmission (CVT) the adaptation process is not done through stepwise changes of the gear ratio. Instead, it is continuously adjusted, and thus eliminates the longitudinal jerk. This characteristic is of importance to transit operators. In the stop-and-go environment, it allows a significant improvement to the comfort of standees.

It also allows a better utilization of the power unit and thus reduces energy consumption. For several years European bus manufacturers and transit properties have been experimenting with this concept. This paper describes the status of the various ongoing effort on CVTs.

2.0 THE VARIOUS TYPES OF CVTs

There are three basic types of CVTs: mechanical, electric and hydraulic. In Exhibit 1 these types have been broken down further to reflect various implementation approaches.

2.1 MECHANICAL CVTs

In a mechanical CVT the speed variation is obtained by modifying the position of an auxiliary element (roller, belt) between two symmetrical surfaces (platen). Exhibits 2 and 3 present two examples of these types of CVTs. The maximum torque that can be transmitted by this type of transmission is a function of the force applied between the rollers and the platen. These transmissions have a fairly high spread. Some of them operate around the unit gear ratio. This implies that a gear assembly is required in series with the CVT to obtain high gear ratio.

These transmissions have been used in the automotive industry (in Europe the DAF passenger car, now Volvo, uses a belt transmission). Few applications are found in urban buses. Recently Leyland introduced a mechanical CVT using semi-toroidal platens and spherical rollers.

2.2 ELECTRICAL CVTs

Several decades ago, the Ward Leonard group pioneered the era of electric regenerative CVTs in fixed installations. Although very interesting, this approach is not applicable to urban vehicles because of its high weight penalty.

To facilitate the discussion on electric CVTs, two cases were identified: on-board power supply (i.e., diesel bus) and wayside power supply (i.e., trolley bus). The following briefly describes the various types of electric CVTs found for each type of application.

2.2.1 Wayside Power Supply

In these applications, the matching function is performed by either a chopper or an AC inverter. At every instant the power supply is matched to the motor input. As with the Ward Leonard, both can be regenerative. I will not discuss this subject further as many of the speakers will address this subject in detail.

2.2.2 On-Board Power Supply

In these applications, several options are possible: the motor-generator set, driven by the IC engine or the cycloconverter. The motor generator approach is, again, very heavy. Furthermore, it does not allow regeneration of the braking energy without a complex set-up. However, it should be mentioned that this approach has been commonly used as an auxiliary propulsion system in several European trolley bus properties. In this case a small IC engine, coupled to a motor-generator set, is used to provide emergency power.

Cycloconverters have also been envisioned. To increase the power/weight ratio, high frequency alternators were used in conjunction with high frequency AC machines. This concept was tested by the Paris Transit Authority (RATP) in the early 1970s. A bus was retrofitted with an experimental cycloconverter. Exhibit 4 presents the overall transmission layout. The weight increase was 1,000 kg (13% of the bus empty weight). Even though it worked well the project was abandoned following a merger involving one of the component suppliers.

2.3 HYDRAULIC CVTs

In a hydraulic CVT a fluid is used to transfer energy between the generator and the driven unit during the adaptation process. This energy transfer process is based on an exchange of either kinetic or potential energy. Where kinetic energy is involved, we are dealing with hydrokinetic transmissions. Where potential energy is involved, we are dealing with hydrostatic transmissions.

2.3.1 Hydrokinetic Transmission

In hydrokinetic transmissions a large flow of fluid is accelerated at high speed by a turbine linked to the generator. The fluid then releases its kinetic energy in another turbine linked to the driven unit. This process, commonly used in torque converters, is ill-suited to meet the requirement of a CVT which must cover a wide range of operating conditions. Thus, no such transmissions are currently under development for the urban bus.

2.3.2 Hydrostatic Transmission

Hydrostatic transmissions use volumetric hydraulic machines. The pump, generally driven by a diesel engine, supplies pressurized hydraulic fluid to one or more hydraulic motors. In turn, the motor drives the wheels or the differential. In most cases, the pump and the motor have variable displacement. The gear ratio is controlled by adjusting the displacement of the hydraulic machines. Exhibit 5 presents a layout of such a transmission. Operation of the hydrostatic transmission is analogous to the operation of a Ward Leonard group. Voltage becomes flow and current becomes pressure. Thus, the maximum pressure (current) in the motor is a function of the maximum torque required at the output shaft and the maximum speed is controlled by the maximum flow (voltage) traversing the motor. Like electric machines, most hydraulic machines are reversible and can easily be used to regenerate braking energy.

Hydraulic machines also have a power-to-weight ratio higher than their electric counterpart. This advantage makes them more attractive to mobile applications. Today they are largely found in the high-torque/low-speed applications, such as earth-moving equipment, shunting locomotives, offshore drilling equipment, military applications and agricultural machinery.

Introduced in the late 1960s the performances of the hydrostatic transmissions improved considerably as experience was gained. These overall improvements as well as the flexibility offered by this new concept, such as the possibility of placing the various elements of the transmission at their most appropriate location and the possiblity of greatly simplifying the implementation of regeneration systems on board autonomous vehicles, has resulted in a flurry of research and development efforts throughout Europe.

Exhibit 6 summarizes these efforts. The following sections detail these activities and the status of their development.

2.3.2.1 Pure Hydrostatic Transmissions

A Pure Hydrostatic Transmission is defined as a transmission in which the hydraulic elements are solely responsible for performing the matching function at all times. The applicability of these transmissions to the urban bus has been investigated in France, Italy, and the United Kingdom.

In these countries prototype transmissions have been retrofitted on a vehicle and have undergone or are currently undergoing revenue service testing.

In the U.K. the prototype transmission was developed by the National Engineering Laboratory (NEL) in East Kilbride, Scotland. It features two hub motors with discretely variable displacement fed by two variable displacement pumps operated in parallel and driven by the diesel engine. This prototype transmission was installed on a Leyland double-decker bus of London Transport in 1976. The arrangement selected by NEL was dictated by the need to improve the transmission efficiency in the vehicle operating range. At the present time, it would appear that the project has stopped. In parallel to this effort, NEL was also developing a small hydrostatic transmission coupled with a small hydropneumatic accumulator to regenerate braking energy. This package was being developed for small cars.

In France development of a hydrostatic drive for an urban bus emanated from the urban bus of the future development program. After conducting a detailed survey of the various components available on the market, an analysis of the impact of this new type of transmission on the overall configuration of the power train and bus structure was conducted by the French Transportation Research Institute. Given the state of technology at the time of the evaluation, it was concluded that the best option was to use a high-speed/low-torque machine in combination with the differential. This approach was recommended because at the time the high-torque/low-speed machines were not appropriate for the urban bus in terms of size, weight, and performances.

Following these recommendations, the Paris Transit Authority started the preliminary design of such a transmission in the late 1970s. This transmission was then retrofitted on a standard Paris bus, the SC10. After a period of fine tuning and testing, the vehicle was assigned to a regular route for a multi-year evaluation program.

To date the vehicle is still running satisfactorily. The smoothness of the transmission is greatly appreciated by the operators and the passengers as well. In the braking mode it was discovered that the transmission behaved as a powerful retarder down to very low speeds resulting in substantial reduction of brake shoe wear.

However, from an energy point of view, the balance turned out to be negative. In spite of this initial setback, which was attributed to the relatively crude control system as well as the inability to obtain the components adapted to this specific application, the Paris Transit Authority decided to pursue the development further by integrating a microprocessor-based control system that would optimize the performance of the transmission while operating the diesel engine along the minimum energy consumption curve. This new package is now being developed and is to be retrofitted on a SC10 and will undergo revenue operation testing in 1984.

In Italy, Mauri installed a similar transmission package on an articulated dual propulsion vehicle. A dual propulsion vehicle is defined as a vehicle having either two different independent propulsion systems or a single propulsion system supplied via two different power sources. The most commonly found dual propulsion configurations are diesel/trolley, battery/trolley, and diesel/battery. The approach chosen by Mauri has allowed the elimination of the chopper. When switching from diesel mode to electric mode, the electric motor is first started at no-load on a resistance. Once it has reached its operating speed, the motor is loaded via the hydrostatic transmission. A control system monitors the maximum current and controls it by adjusting the pressure in the hydraulic circuit. The vehicle has been undergoing testing since 1981.

While encouraging, these preliminary results obtained throughout Europe indicate that development efforts are still needed to improve the operating efficiency of this configuration. One of the most sensitive areas is the low efficiency of the transmission under partial load conditions. The relatively small spread (5) that can be achieved with the present technology is at the origin of the problem. To paliate these limitations, new configurations and new component developments are taking place. For example, the configuration shown in Exhibits 7 and 8 represents some of the evolutions that are presently being investigated. The addition of a third hydraulic machine that works either as a motor when high torques are required (such as starting or climbing grades) or as a pump when high flows are required (such as high speed running) has increased the spread of the transmission without altering the average efficiency. This wider spread allows to properly select operating conditions of the hydraulic components in the entire operating range of the vehicle without the losses previously encountered. As can be seen in Exhibits 7 and 8 this configuration requires mechanical entrainment of the extra hydraulic machine by either the input or the output shaft. This reduces the flexibility of implementation mentioned earlier. A transmission based on the principle described in Exhibit 8 is presently undergoing bench testing in France.

The approach described above has the advantage of substantially improving the operating characteristics of the transmission using off-the-shelf components; however, it introduces change of mode which requires that specific precaution to be taken when changing from one configuration to the other.

A second approach is to develop hydraulic components with improved performances. This path is also being followed. For example, in France, development of a new type of high-torque hub motor is being sponsored by various government agencies. This motor is a radical departure from the traditional piston type machine. It offers a vibration-free operation and a high power-to-weight ratio. A prototype of this motor with continously variable displacement is about to undergo bench testing.

In parallel to the development of pure hydrostatic transmissions other developments are taking place with a so-called split power transmissions.

The following section describes these transmissions and the status of their development.

2.3.2.2 Split Power Transmissions

These transmissions combine epicyclic gear trains and hydrostatic transmissions. Exhibit 9 presents the general layout of such a transmission. The hydraulic elements are used to control the torque applied to the ring gears of the epicyclic trains. They replace the traditional control brakes. By progressively transferring the torque required to immobilize the ring gear of a given train to the next train, a smooth speed variation between the fixed ratio of each gear train is obtained. Furthermore, this maneuver is done by tapping only a fraction of the total power flowing through the transmission. In most cases, the maximum power bypassed through the hydrostatic transmission ranges between 20% and 30% of the total power. When compared to a pure hydrostatic transmission, this configuration exhibits a better overall efficiency because most of the power is transferred mechanically at all times. To date the development of such transmissions for urban buses is very active in France and Germany.

The French Efforts

Two distinct R&D programs are being pursued. One is conducted by Renault Vehicules Industriels and the other by Moteur Moderne.

The Renault Project -- code named AUROCH -- is aimed at developing a CVT for the urban bus. The hydraulic machines used in the transmission can also be operated in conjunction with an on-board hydropneumatic energy storage system. To simplify the design, the torque converter has been kept for operating speed below 10 mph. A prototype of the transmission has been built and bench tested in the spring of 1983. The transmission is to be retrofitted on a vehicle and to start road testing during 1984.

The Moteur Moderne Project is more complex. The transmission consists of three epicyclic trains and one hydrostatic transmission. A prototype was built with off-the-shelf components and bench tested. The test results indicated that the transmission had a better partial load efficiency than pure hydrostatic transmission. Further testing has been planned to investigate transient conditions and to define the optimum control laws.

The German Program

In Germany MAN has taken a leading role in the development of split power transmissions. These efforts are a direct result of the company's extensive involvement in energy storage and regeneration suba transmission and retrofitted it on a vehicle for endurance testing. So far the results of the tests indicate that the energy consumption is as good as the one obtained with the best conventional transmission. When a change of mode occurs, the longitudinal jerk is comparable to that observed on the automatic gear boxes.

Besides these applications, R&D activities concerned with vehicle translation are being pursued in the area of energy storage. In this case the CVT can either have single or multiple function, i.e. provide the interface between the engine and the wheel and/or between the wheel and the storage system. The following section summarizes the major programs involving these specific uses.

2.3.2.3 CVTs and On-Board Energy Storage

The most commonly found energy storage systems are the flywheel and the hydropneumatic accumulators. Because of their specific operating characteristics, their application to urban vehicles requires the utilization of a CVT. To date, because of their extreme flexibility and their relative ease of control, hydrostatic transmissions have been largely used to perform the matching function between the vehicle and the storage system. The bulk of the activity on storage systems for autonomous vehicles is taking place in France, Germany and Sweden. Other efforts took (or are about to take) place in Denmark, Italy, and in the United Kingdom.

Of all the remaining active programs, the German one has been the most systematic. Four various configurations were investigated. In the first one (Hydrobus I) a pure hydrostatic transmission was geared to the output of the transmission and was used solely to interface with hydropneumatic accumulators. The three other configurations use split power transmissions with a dual role (vehicle translation and interface with the storage system). These included the Gyrobus I (high energy flywheel -- program terminated), the Gyrobus II (low energy flywheel -- undergoing program) and the Hydrobus II (concept).

In France, the R&D effort is conducted by Renault, in parallel with the development of their split power transmission. Energy storage will be done via a hydropneumatic accumulator. The system, designed to deliver up to 220 kW during the acceleration phase, has yet to be tested. Plans call for testing during 1984.

In Sweden, Volvo developed a pure hydrostatic transmission that interfaced between the differential and a flywheel used as a buffer. This extremely attractive configuration was retrofitted on an urban bus for road testing. The results of the test indicated that substantial energy savings were achieved (22% to 24%), even though the transmission/flywheel package is heavier than a standard transmission.

In Denmark, a CVT was used as the interface between a hydropneumatic storage system and the output of a regular transmission (concept similar to the Hydrobus I). Even though the results obtained were encouraging, the project was shelved.

In Italy, Fiat is investigating a flywheel energy storage system in an effort that parallels the development of a hybrid bus. This effort is still in its early stage of development.

In the United Kingdom, the NEL used a pure hydrostatic CVT as an interface with hydropneumatic accumulators. This project was oriented toward small vehicles. At the present time it would appear that the project has been shelved. In parallel with the development of its mechanical CVT, Leyland is investigating a flywheel storage system.

3.0 OUTLOOK

Still in early development, CVTs should become a reality in the near future. They could bring to the diesel bus what the chopper has brought to the electric vehicle: elimination of jerk during acceleration, reduced energy consumption and possible integration into a regeneration scheme. Like the early chopper, CVTs will have to go through a somewhat long maturation process before they can compete with the traditional transmission. They have to trim weight and show that they can be as reliable as those in service today. These two goals present the major challenge to the designers. However, if one looks back at the history of the chopper, there is ample reason to be optimistic.

BIBLIOGRAPHY

Besson, B. and J. M. Blanquet. "Transmission à Dérivation de Puissance Hydrostatique. Conception et Essais d'Une Maquette Expérimentale, Resultats Acquis et Perspectives", Revue des Ingénieurs de l'Automobile, Janvier 1979.

Dunoyé, Daniel and Georges Bonnardel. "Transmission Hydrostatique-Application à l'Autobus Urbain", Institut de Recherche des Transports, Arcueil, June 1977.

Hydrostatic Transmissions for Vehicle Application, Proceedings of the European Conference at the University of Warwick, September 1981.

Journées Internationales "Hydrauliques", Proceedings of the Conference in Angers, May 1983.

Pichard, J. and B. Besson. "Proposition d'Un Modèle général Représentatif des Transmissions de Puissance, Exemple d'Exploitation", Revue des Ingénieurs de l'Automobile, Avril 1977.

Scott, David. "Heavy Duty CVT Has Traction-Roller Drive", Automotive Engineering, Vol. 91, No. 7, July 1983.

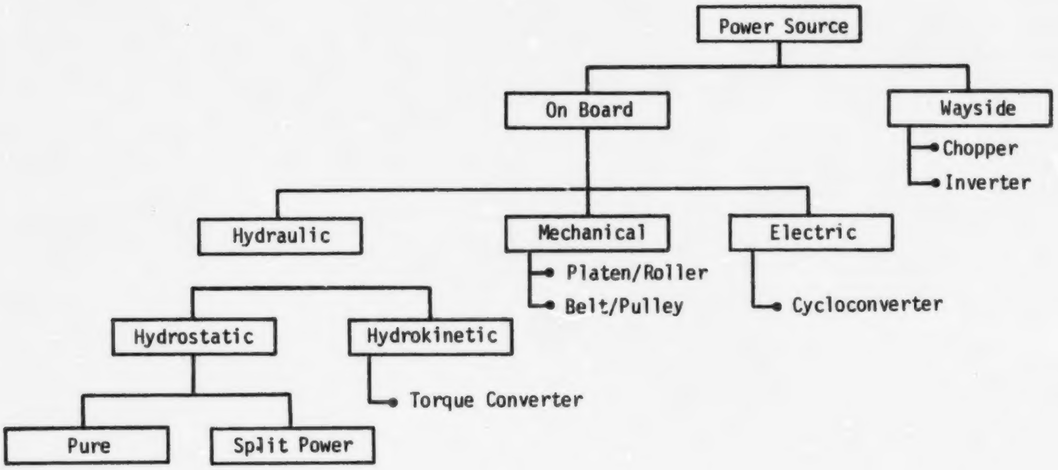

Power Source
On Board
Wayside
Chopper
Inverter
Hydraulic
Mechanical
Electric
Platen/Roller
Belt/Pulley
Cycloconverter
Hydrostatic
Hydrokinetic
Torque Converter
Pure
Split Power

EXHIBIT 2: Semi-Toroidal Mechanical CVT

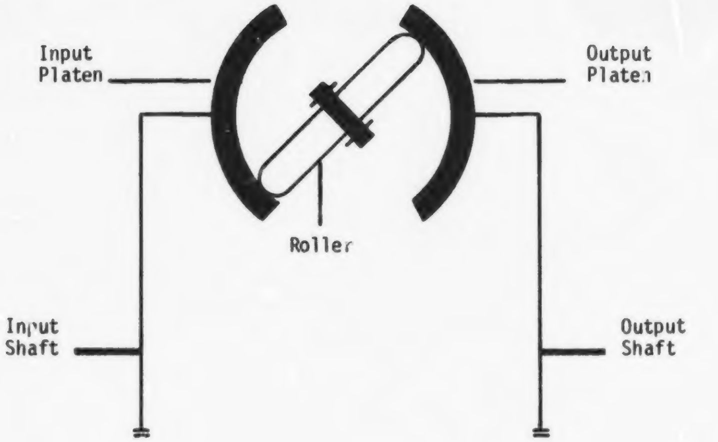
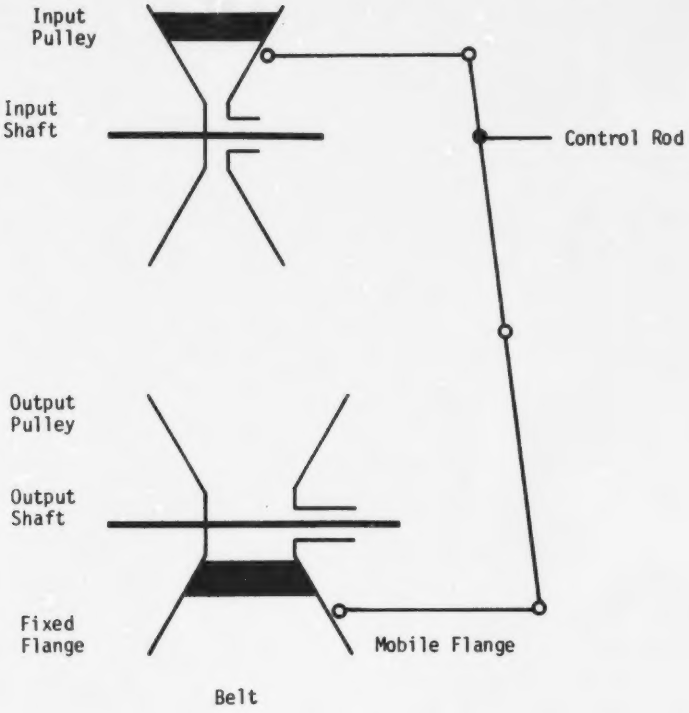

Input Platen
Output Platen
Roller
Input Shaft
Output Shaft

EXHIBIT 3: Belt CVT


Input Pulley
Input Shaft
Control Rod
Output Pulley
Output Shaft
Fixed Flange
Mobile Flange
Belt

Pushing or pulling the control rod changes the positions of both mobile flanges; forcing the belt to change position and thus change the gear ratio.

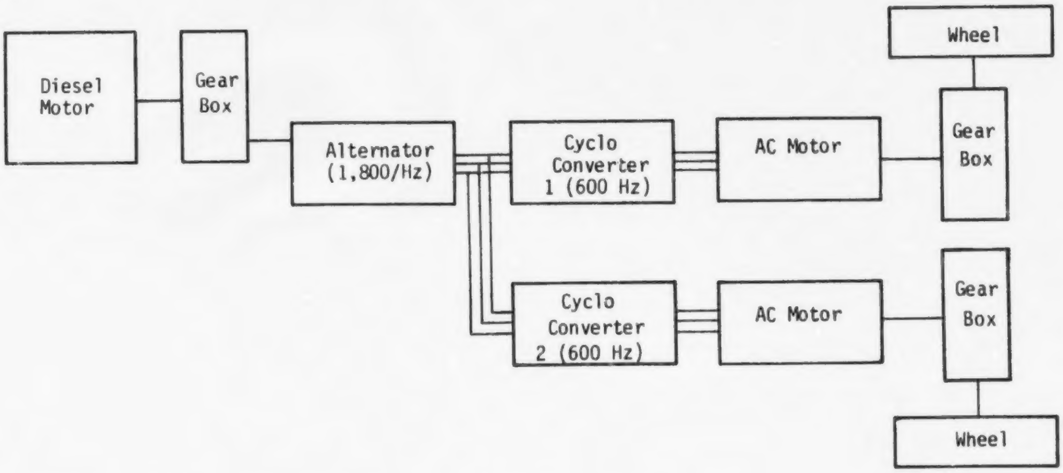

Diesel Motor
Gear Box
Alternator (1,800/Hz)
Cyclo Converter 1 (600 Hz)
AC Motor
Gear Box
Wheel
Cyclo Converter 2 (600 Hz)
AC Motor
Gear Box
Wheel

EXHIBIT 4: Layout of the Electric Transmission that was Retrofitted on a Paris Authority Transit Bus.

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EXHIBIT 5: Basic Layout of a Hydrostatic Transmission

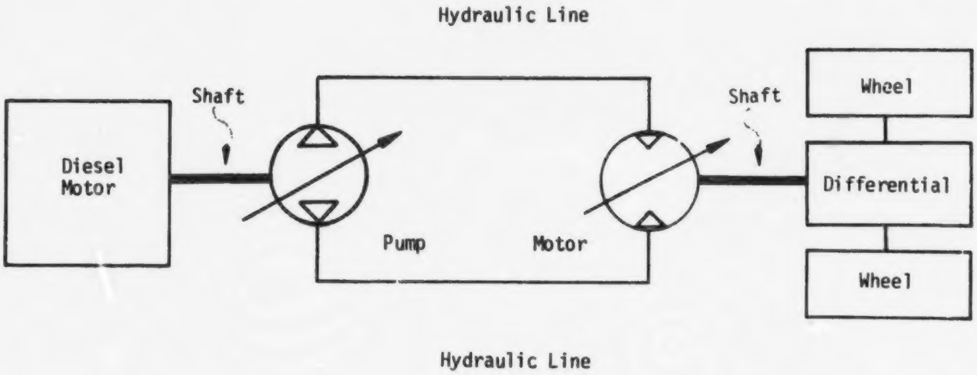

Hydraulic Line
Shaft
Diesel Motor
Shaft
Wheel
Differential
Pump
Motor
Wheel
Hydraulic Line

EXHIBIT 6:

CONTINOUSLY VARIABLE
TRANSMISSIONS
Summary of the European R&D efforts

TYPE	CLASS	USE	STATUS	# OF UNITS	DEVELOPER	NOTES
CONTINUOUSLY VARIABLE	PURE HYDROSTATIC	VEHICLE TRANSLATION	PROTOTYPE	2; mounted on a SC10 urban bus; operated regular routes in Paris.	PARIS TRANSIT AUTHORITY	Uses high speed/low torques off the self machines. Similar configuration being considered by Heuliez for its new buses.
CONTINUOUSLY VARIABLE	PURE HYDROSTATIC	VEHICLE TRANSLATION	PROTOTYPE	1; mounted on an articulated dual propulsion trolley bus undergoing test in Milan	MAURI (bus body designer and manufacturer)	Uses high speed/low torques off the self machines. The vehicle has two such transmissions, one for each propulsion configuration
CONTINUOUSLY VARIABLE	PURE HYDROSTATIC	VEHICLE TRANSLATION	PROTOTYPE	1; mounted on a double decker of London Transport.	National Engineering Laboratory	Uses high speed/low torques pumps and two hub motors with discratly variable displacement. It would appear tha the R&D effort has ceased.
CONTINUOUSLY VARIABLE	PURE HYDROSTATIC	VEHICLE TRANSLATION	PROTOTYPE	1; mounted on a test bench	Poclain Hydraulics	This transmission combines three machines. The middle one is entrained by the output shaft to work as a motor. It can be coupled to the input shaft and thus work as a pump. This configuration increases the transmission range.
CONTINUOUSLY VARIABLE	PURE HYDROSTATIC	VEHICLE TRANSLATION AND ENERGY STORAGE	PROTOTYPE	1, mounted on a Volvo bus	Volvo	Uses three high speed low torque machines The transmission is installed between the flywheel and the differential. The motor drives the flywheel

EXHIBIT 6: Continued

CONTINOUSLY VARIABLE
TRANSMISSIONS
Summary of the European R&D efforts

TYPE	CLASS	USE	STATUS	# OF UNITS	DEVELOPER	NOTES
CONTINUOUSLY VARIABLE	PURE HYDROSTATIC	ENERGY STORAGE	PROTOTYPE	1 mounted on a Leyland	Univesity of Denmark	Uses two high speed low torque machines that are driven by the transmission out put shaft. It appears that the program has been selved.
CONTINUOUSLY VARIABLE	SPLIT POWER PATH (Hydrostatic transmission combined with epicyclic gear	VEHICLE TRANSLATION AND ENERGY STORAGE	PROTOTYPE	1, presently on a test bench. To be mounted on a bus in 1984	Renault Vehicules Industriels.	Uses a single epicyclic gear train and single hydrostatic transmission. The torque converter has been kept.
CONTINUOUSLY VARIABLE	SPLIT POWER PATH (Hydrostatic transmission combined with epicyclic gear	VEHICLE TRANSLATION AND ENERGY STORAGE	PROTOTYPE	1, presently on a vehicule, undergoin extensive road test	MAN	Uses a single epicyclic gear train and single hydrostatic transmission. The torque converter has been eliminated.
CONTINUOUSLY VARIABLE	SPLIT POWER PATH (Hydrostatic transmission combined with epicyclic gear	VEHICLE TRANSLATION	PROTOTYPE	1, on a test bench.	Moteur Moderne	Uses two epicyclic gear trains and a single hydrostatic transmission
CONTINUOUSLY VARIABLE	MECHANICAL	VEHICLE TRANSLATION	PROTOTYPE	1, on a test bench.	Leyland	Uses two semi-toroidal platen and spherical rollers

EXHIBIT 7: Hydrostatic Transmission with Motor/Pump Unit Permanently Attached to the Transmission Output Shaft.

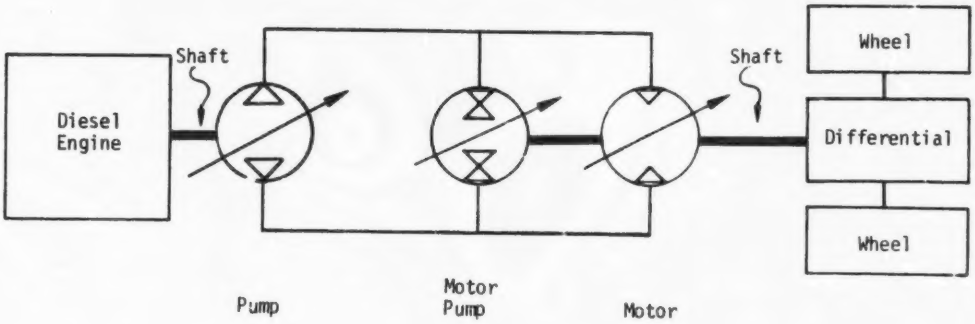


EXHIBIT 8: Hydrostatic Transmission with the Motor/Pump Unit Coupled Either to the Input Shaft (High Speed Running) or the Output Shaft (High Torque).

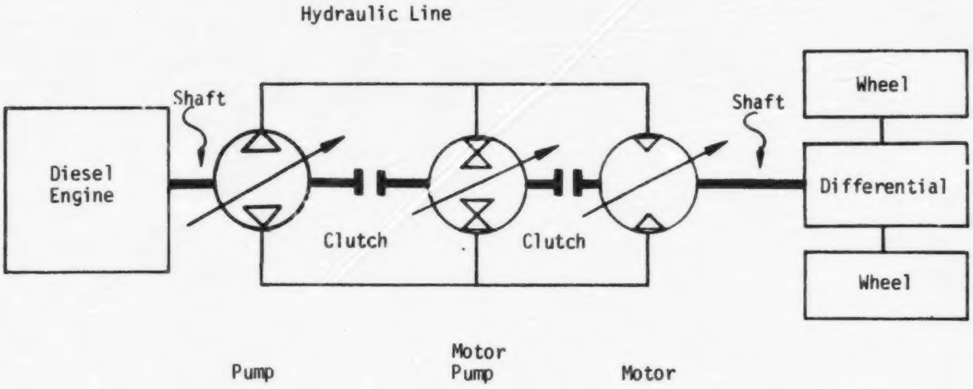
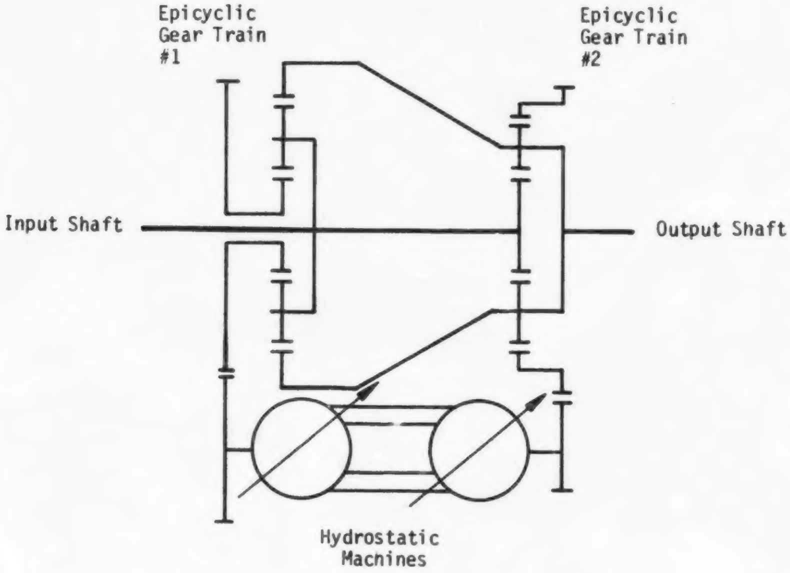

Hydraulic Line
Shaft
Diesel Engine
Clutch
Clutch
Shaft
Wheel
Differential
Wheel
Pump
Motor Pump
Motor

EXHIBIT 9: Layout of a Split Power Transmission


Epicyclic Gear Train #1
Epicyclic Gear Train #2
Input Shaft
Output Shaft
Hydrostatic Machines

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